NATIONAL
URANIUM
TAILINGS
PROGRAM

URANIUM TAILINGS SAMPLING MANUAL

NUTP-1E

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Golder Associates: *S. Feenstra, D.W. Reades, J.A. Cherry*
and
SENES Consultants: *D.B. Chambers, G.G. Case,*
B.G. Ibbotson

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FOREWORD

There are currently about 130 million tonnes of mine wastes (tailings) produced from the mining and milling of uranium ore that are on, or near, the surface in Canada. At public hearings and other forums held in connection with proposals for new uranium production facilities, concern has been expressed about the impact that these wastes may have on the environment in the future. Government regulatory agencies believe that there may be long-term environmental and health consequences associated with uranium tailings that are not yet fully understood.

As a result of a year-long study, undertaken by a group of experts from government, industry, and the universities, into the possible long-term problems of uranium tailings management, the decision was taken by the Federal Government to launch an R & D program to assist in clarifying the nature and extent of problems that may arise in the future. It is anticipated that the results of such a program will be of use to the Atomic Energy Control Board and to provincial regulatory agencies in the establishment of criteria for the decommissioning and abandonment of uranium tailings. To this end, the National Uranium Tailings Program of CANMET has been funded to the extent of $9.5 million for a period of five years.

The main objective of this Program is to provide a scientifically credible information base that will assist government regulatory agencies in making confident, knowledgeable decisions, and in establishing criteria for the long-term protection of the environment and human health. The scientific information base will, among other things, describe the chemical and physical processes that involve tailings constituents and their movement along pathways from the tailings into the biosphere.

The National Uranium Tailings Program's activities, which have been entirely contracted out, have included research into the processes involved in the behaviour and movement of contaminants from tailings, field sampling and measurements, chemical analyses, and predictive modelling. As an important part of the Program output, manuals have been prepared that incorporate the results of this work.

This manual has been prepared for the purpose of making available up-to-date information and data that will be of interest and practical use to those directly concerned with operational aspects of uranium tailings management and regulation.

W.G. Jeffery
Director General
Canada Centre for Mineral and Energy
Technology

PREFACE

This manual was prepared under contract to the National Uranium Tailings Program (NUTP). NUTP is a federally-funded research program designed, among other things, to obtain data and information on uranium tailings constituents with the purpose of predicting the probabilities of contaminant releases and their impact on the environment in the long-term. It is essential that any samples taken during a field program on behalf of NUTP should be collected in the most scientific and accurate way possible. It is also important that any contractor working on behalf of NUTP uses sampling techniques that meet the quality standards required for the Program. For this reason, NUTP staff commissioned this manual, one of a series of manuals, to ensure that an acceptable reference is available. It is also hoped that this manual will be useful to others working on field sampling programs.

ACKNOWLEDGEMENTS

As with any such endeavour, a large number of people made many helpful contributions to the development of this manual. I would like to thank the staff of NUTP, Victor Haw, Walter Harrison, Grant Feasby, and Gilles Tremblay for their input. I would particularly like to thank Garry Grove of the National Hydrological Research Institute, Environment Canada, for all his many efforts. Lastly, I would like to thank Doug Chambers, Glen Case, Bret Ibbotson of SENES Consultants, and John Cherry and the two principal authors, Stan Feenstra and Denys Reades of Golder Associates.

Roy John
Project Manager, Measurements
National Uranium Tailings Program

DISCLAIMER

Any mention of, or reference to, manufacturers' products should not be construed as an endorsement for those specific products.

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1. INTRODUCTION

1.1 PURPOSE OF SAMPLING MANUAL

The purpose of this manual is to describe the requisite sampling procedures for the application of uniform high-quality standards to detailed geotechnical, hydrogeological, geochemical and air quality measurements at Canadian uranium tailings disposal sites. The selection and implementation of applicable sampling procedures for such measurements at uranium tailings disposal sites are complicated by two primary factors.

Firstly, the physical and chemical nature of uranium mine tailings and effluent is considerably different from natural soil materials and natural waters. Consequently, many conventional methods for the collection and analysis of natural soils and waters are not directly applicable to tailings. Secondly, there is a wide range in the physical and chemical nature of uranium tailings. The composition of the ore, the milling process, the nature of tailings deposition, and effluent treatment vary considerably and are highly site-specific. Therefore, the definition and implementation of sampling programs for uranium tailings disposal sites require considerable evaluation, and often innovation, to ensure that appropriate sampling and analysis methods are used which provide the flexibility to take into account site-specific considerations.

The following chapters describe the objective and scope of a sampling program, preliminary data collection, and the procedures for sampling of tailings solids, surface water and seepage, tailings porewater, and wind-blown dust and radon.

1.2 URANIUM MINE TAILINGS IN CANADA

Uranium mining and milling operations began in the Northwest Territories in 1943 and have been conducted in Ontario and northern Saskatchewan since the mid 1950's. Since that time, 19 uranium mining operations have produced approximately 126 million tonnes of tailings. Of this total, approximately 117 million tonnes have been deposited in a variety of surface impoundments covering a total of 635 ha, with the remainder deposited underwater in lakes or used as mine backfill. The bulk of the uranium mine tailings, 81 per cent (102 million tonnes), are located in the Elliot Lake area of Ontario. Approximately 14 per cent (18 million tonnes) are located in northern Saskatchewan and 5 per cent (6 million tonnes) are located in the Bancroft area of Ontario.

Of the total quantity of tailings, approximately 34 per cent, or 43 million tonnes, are located in inactive or decommissioned tailings impoundments which no longer receive tailings. The majority of these tailings impoundments were operated from the mid 1950's to the mid 1960's and have been inactive since that time. The remaining 66 per cent or 83 million tonnes of tailings are located in active tailings impoundments which currently receive tailings. With the exception of the Eldorado Nuclear Limited (now called Eldorado Resources Ltd.) Beaverlodge operation which used an alkaline-leach process, all the mine-mill operations used an acid-leach process for the extraction of uranium from the ore. At the present time there are seven operating mines in Elliot Lake and northern Saskatchewan which produce approximately 7 million tonnes of tailings per year.

The various active and inactive tailings impoundments in Ontario and northern Saskatchewan vary considerably in character due to differences in size, age, construction of the tailings impoundment and composition of the tailings, as well as regional differences in climate and physiographic setting. These variations make each tailings impoundment unique in terms of the specific considerations for the detailed design and implementation of sampling programs.

The uranium tailings impoundments in Canada range in size from the small inactive Dyno tailings impoundment at Bancroft which covers 4 ha and contains only 0.36 million tonnes of tailings, to the active Long Lake tailings impoundment at Elliot Lake which covers 125 ha and contains 40 million tonnes of tailings. The Nordic tailings impoundment at Elliot Lake is currently the largest inactive tailings impoundment covering 107 ha and containing 10.9 million tonnes of tailings.

There is also considerable variation in the age of various tailings impoundments. For example, the Dyno tailings impoundment only operated for a short period from 1958 to 1960 whereas the Long Lake tailings impoundment has been in continuous operation since 1959. The Rabbit Lake tailings impoundment in northern Saskatchewan did not begin operations until 1975. The wide ranges in size and age of the uranium tailings impoundments naturally result in differences in the designs of the impoundments, the methods of tailings deposition and the types of milling process at the various sites. The specific importance of these differences to the design of sampling programs will be described in the following sections for the different components of a sampling program.

There is a considerable variation in the chemical and mineralogical composition of the tailings due to differences in the ore derived from the different mines, and differences in the milling and treatment processes. Ore deposits in the Elliot Lake area are large, relatively low-grade deposits with uranium and thorium occurring in brannerite, uraninite and monazite minerals. The principal accessory metallic mineral in the Elliot Lake ores is pyrite (iron sulfide). In contrast, the recently developed northern Saskatchewan ore deposits are typically small, high-grade deposits with uranium occurring in pitchblende but with little thorium. These deposits typically have substantial quantities of accessory metallic minerals such as gersdorffite (nickel arsenic sulfide) cobaltite (cobalt arsenic sulfide) and millerite (nickel sulfide). These accessory minerals can have a considerable effect on the chemical composition of the tailings. The specific importance of the differences in the composition of the tailings to the design of sampling programs will be described for the different components of a sampling program.

1.3 PRINCIPAL ENVIRONMENTAL CONCERNS

The principal environmental concerns related to uranium tailings impoundments arise from the potential movement of chemical and/or radioactive constituents out of the tailings impoundments into the surrounding environment. The major pathways for the movement of chemical and/or radioactive constituents out of a tailings impoundment are shown in Fig. 1.1. These pathways include:

- surface water runoff from the tailings impoundment;
- localized seepage from within the tailings into surrounding surface water;
- exfiltration of porewater from the tailings into the underlying groundwater system;
- removal of tailings as wind-blown dust;
- exhalation of radon from the tailings into the atmosphere.

In this report, *seepage* refers to tailings porewater that emerges from the tailings and discharges to surface water in the immediate vicinity of the tailings impoundment. *Exfiltration* refers to tailings porewater that moves out of the tailings and enters the groundwater system underlying the tailings impoundment.

Because of the considerable variation in different tailings impoundments, any combination of these mechanisms may be applicable to a particular tailings impoundment. The following are examples of various uranium tailings impoundments at which these pathways have been evaluated.

Surface Water Runoff

The effects of surface water runoff and erosion at the inactive Gunnar tailings impoundment in northern Saskatchewan have increased the total suspended solids, total dissolved solids and various radionuclide concentrations in Langley Bay (Swanson and Abouguendia, 1981). As a result, the aquatic biota of Langley Bay are bioconcentrating radionuclides.

Seepage

Localized seepage of contaminated water from tailings into surface water through pervious retaining dams has been documented at the inactive Stanrock tailings impoundment at Elliot Lake (Feenstra et al., 1981). The chemical composition of seepage emerging from the dams has been strongly influenced by the oxidation of pyrite within the tailings, and is

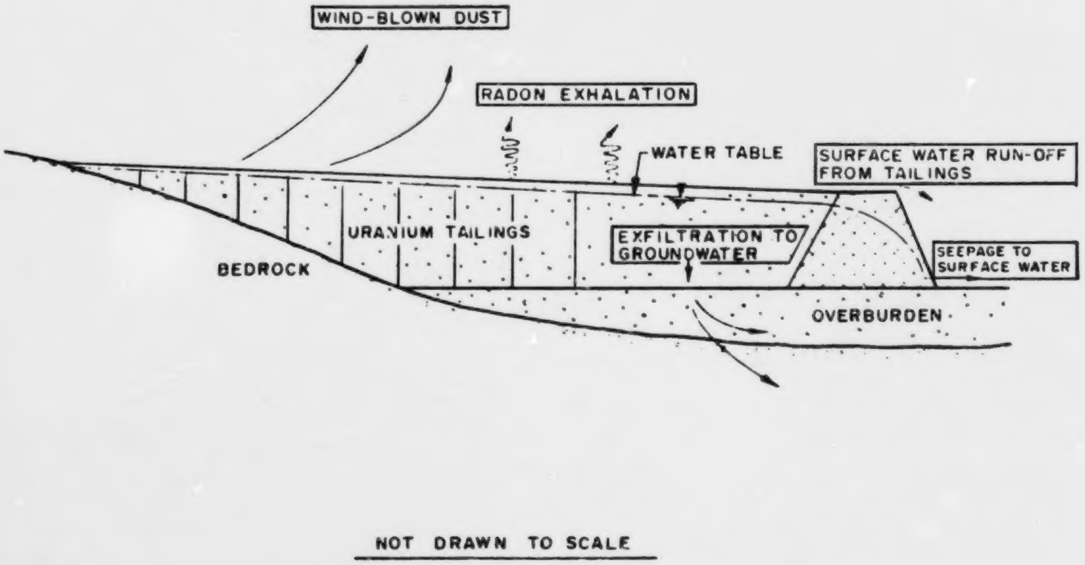

Fig. 1.1 – Potential environmental concerns at uranium tailings impoundments

characterized by low pH (2-3) and high concentrations of iron and sulfate (up to 2000 mg/L and 6000 mg/L respectively). The seepage from the Stanrock impoundment is currently collected and treated prior to discharge.

Exfiltration

The exfiltration of contaminated water from tailings into the underlying groundwater systems has been documented at the inactive Nordic tailings impoundment at Elliot Lake (Cherry et al., 1980; Morin et al., 1982). The chemical composition of porewater from the tailings has been strongly influenced by the oxidation of pyrite within the tailings and this porewater has moved down into an underlying sand aquifer. The exfiltration of porewater from the tailings into the groundwater has resulted in an extensive contaminant plume in the aquifer, characterized by high concentrations of iron and sulfate (500 mg/L and 3000 mg/L respectively), which is migrating at the velocity of the groundwater. In addition, there exists an inner, smaller, more highly contaminated plume, characterized by low pH (<4) and elevated concentrations of heavy metals, radium-226, iron, and sulfate (several mg/L, 4.5 Bq/L, 5000 mg/L and 12 000 mg/L respectively), but which is migrating at less than one per cent of the groundwater velocity due to chemical attenuation in the aquifer.

Wind-blown Dust

About 16 per cent of the measurements of suspended particulate matter, made at the inactive Stanrock tailings impoundment at Elliot Lake during June to September 1977 (James F. MacLaren Ltd., 1978), exceeded Environment Canada's 24-hour suspended particulate air quality criterion (120 $\mu g/m^3$) at stations within 100 m of the tailings impoundment.

Radon Exhalation

Radon exhalation measurements at the inactive Nordic tailings impoundment at Elliot Lake ranged from 4.5 to 14.5 $Bq/m^2/s$ (James F. MacLaren Ltd., 1978). These radon exhalation rates are approximately two orders of magnitude greater than exhalation rates on native soils in the Elliot Lake area.

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2. DEFINITION OF A SAMPLING PROGRAM

2.1 OBJECTIVES

The overall objective of a sampling program at a uranium tailings impoundment is to effectively characterize the appropriate components of the physical and chemical environment in and around the impoundment. This characterization could be intended to fulfill regulatory requirements regarding the potential environmental impact of the tailings impoundment, to provide a basis for the design of remedial measures or reclamation programs, or to contribute to basic research on uranium tailings. The important components of the physical and chemical environment of the tailings impoundment include:

- physical, chemical, mineralogical and radiological characteristics of the tailings solids;
- chemical and radiological characteristics of the tailings porewater;
- physical, chemical and radiological characteristics of surface water flow from, and seepage out of, the tailings impoundment;
- hydrogeological conditions within and around the tailings impoundment and the characteristics of exfiltration out of the tailings;
- air quality and meteorological conditions over and around the tailings impoundment.

The tailings solids and tailings porewater are the sources for potential chemical and radiological contamination, and as described in Section 1.3, surface water flow, seepage, exfiltration, wind-blown dust and radon exhalation are the potential pathways for the movement of contaminants out of the tailings impoundment.

2.2 SCOPE

The overall scope or level of effort applied to a sampling program for a uranium tailings impoundment depends primarily on the purpose of the sampling program. Sampling programs intended to contribute to basic tailings research or to provide a basis for the design of remedial or reclamation programs may be generally more detailed and extensive than sampling programs intended to fulfill monitoring requirements for regulatory agencies.

As noted in the preceeding discussions, there is a wide variation in the character of uranium tailings impoundments and the nature of environmental concerns, and consequently sampling programs must generally be designed to be site-specific. The detailed scope of a sampling program will depend on the nature and complexity of the physical and chemical environment in and around the tailings impoundment, and the nature and severity of the potential environmental concerns. For example, a tailings impoundment into which tailings have been discharged from several locations around the impoundment may require more extensive sampling to characterize the impoundment compared to an impoundment into which tailings were deposited from a single location. Similarly, a sampling program for a tailings impoundment which is partially submerged or vegetated may not emphasize the sampling of wind-blown dust as may a sampling program for a dry unvegetated impoundment.

More detailed discussions regarding the scope of a sampling program are found in the following chapters which relate to the different components of a sampling program.

3. PRELIMINARY DATA COLLECTION

The initial step in the design and implementation of a sampling program is the collection of all applicable background data regarding the uranium tailings impoundment. These data include information on the physical, chemical, hydrologic, meteorological and operational aspects of the tailings impoundment and can be obtained from a variety of sources such as mine-mill records and personnel, aerial photographs, and government records. The various types and possible sources for these background data are summarized in Table 3.1.

These data are used for the design of a sampling program and the evaluation of the results of a sampling program. For example, information on the depositional history of a tailings impoundment operated in the 1950's is generally not included in the mine-mill records. In the absence of recorded data on information such as this, interviews with past mine-mill personnel and archival aerial photographs can be useful to provide this information. Information such as the tailings discharge locations and consequently approximate delineation of the areas of coarse- and fine-grained tailings is valuable in the selection of tailings sampling locations and the selection of sampling methods.

At the present time, CANMET is sponsoring the development of a computer database for uranium mine tailings. The database will be named CANUT (Canadian Uranium Tailings) and will ultimately include operational history and results of water, soil and biological sampling at uranium tailings impoundments in Canada. This database, when developed, will be extremely valuable for the collection of much of the noted background data.

Table 3.1 – Types and sources of background data

Type	Source
1. Physical and Chemical	
(a) Present topography of tailings and surrounding area	Mine-Mill records Government mapping Recent aerial photographs
(b) Topography underlying tailings area	Mine-Mill records Government mapping Archival aerial photographs
(c) Local and regional geological conditions of overburden and bedrock	Mine records Exploration drilling and mapping Government mapping
(d) Chemical composition and mineralogy of the ore.	Mine-Mill records Published research
2. Hydrologic	
(a) Local and regional hydrologic data on drainage patterns, streamflow, runoff, lake levels, precipitation, evapotranspiration, water quality	Government records Mine-Mill records
(b) Local and regional hydrogeological data on groundwater levels, groundwater quality and uses.	Government records Exploration drilling Mine-Mill records
3. Meteorological	
(a) Climatic records on temperature, windspeed and wind direction	Government records Mine-Mill records
(b) Air quality and dustfall.	Government records Mine-Mill records
4. Operational	
(a) Present and past milling and extraction processes. In particular: ore grade, reagents used, production rates, effluent treatment	Mine-Mill records Present and past mine-mill personnel
(b) History of tailings deposition. In particular: discharge locations, spills, revegetation, surface treatment	Mine-Mill records Present and past mine-mill personnel Archival aerial photographs
(c) Physical and chemical character of tailings discharge and decant.	Mine-Mill records Government records Present and past mine-mill personnel

4. TAILINGS SOLIDS

4.1 OBJECTIVES

The overall objective of tailings solids sampling is to characterize the physical and chemical properties of the tailings solids. The properties of the tailings solids will influence:

- quantity and quality of surface water runoff;
- quantity and quality of seepage and exfiltration;
- quantity and quality of wind-blown dust;
- radon exhalation.

The tailings solids provide the principal source for potential chemical and radiological contamination but also provide important controls on the pathways by which contaminants can exit tailings impoundments.

The physical properties of the tailings solids such as grain size and permeability will influence the quantity of surface water runoff, seepage and exfiltration from the tailings impoundments. For example, in an area of a tailings impoundment with silty tailings of relatively low permeability (10^{-6} cm/s or less), seepage and exfiltration out of the impoundment will be restricted while surface water runoff from the impoundment will be enhanced compared to those areas characterized by highly permeable sandy tailings (10^{-4} cm/s or greater). The grain size of the tailings solids will influence the quantity of wind-blown dust removed from the tailings impoundment. Fine-grained tailings particles may be more readily removed from the surface of the tailings unless they remain wet and/or form a crust. The grain size and water retention characteristics of the tailings solids will influence the degree of radon exhalation from the tailings impoundments, because radon exhalation is inhibited in wet, fine-grained tailings. In addition, physical properties such as density and shear strength of the tailings are important in the consideration of future settlement of the tailings and/or the overall stability of the tailings impoundments.

Although the chemical quality of surface water runoff, seepage and exfiltration from tailings impoundments is influenced by the chemical composition of the liquid mill effluent, it may also be strongly influenced by chemical reactions which occur in the tailings due to the chemical and mineralogical nature of the tailings solids.

For example, in chemically unbuffered (low acid neutralization capacity) tailings which contain significant concentrations of sulfide minerals (high acid generation capacity), sulfide mineral oxidation can occur close to the surface of tailings. These conditions may be reflected in poor quality runoff, seepage and exfiltration from tailings impoundments.

The chemical composition of the tailings solids is also reflected in the chemical composition of wind-blown dust removed from the tailings impoundment. The radionuclide activities in the tailings solids and any resultant wind-blown dust are of particular concern. Similarly, the radium-226 activity of the tailings strongly influences the potential radon exhalation from the tailings impoundment. Higher radium-226 activities increase potential radon exhalation.

The following discussions consider equipment and procedures for sampling tailings solids to determine their principal physical and chemical properties. General geophysical techniques which might be used to determine characteristics such as the thickness and volume of tailings in an impoundment are not discussed in this manual. Details of the principles and application of geophysical techniques in subsurface investigations are found in Telford et al. (1976). Similarly, sophisticated sampling and testing procedures for an assessment of the susceptibility of tailings to liquefaction are not considered in this manual. Such test procedures are described in American Society of Civil Engineers (ASCE) (1981) and (1982). Lastly, the sampling of natural soils or the bedrock beneath a tailings impoundment is not discussed in this manual.

A general overview of designing subsurface investigations, field investigation methods and reporting is given by ASCE (1976). Detailed subsurface investigation methods are reviewed by Naval Facilities Engineering Command (NAVFAC) (1982) and U.S. Department of the Interior (1974).

4.2 SELECTION OF SAMPLING LOCATIONS

Locations for the sampling of tailings solids should be selected in order that the samples are representative of the conditions within the tailings impoundment. The sampling locations must be distributed both areally and vertically throughout the tailings impoundment to allow adequate definition of the spatial variability in the character of the tailings solids. Tailings are generally discharged to the impoundments as a slurry of low solids density (less than 50 per cent) and may thus undergo considerable segregation during deposition. The coarser grained sandy tailings are generally deposited close to the point of discharge whereas the finer grained silty tailings are usually deposited away from the discharge. In addition, at any given location within the tailings there may be considerable interlayering of sandy and silty tailings as depositional conditions vary. Depositional conditions may vary as a result of changes in the rate of the tailings discharge and changes in the location of the tailings discharge points. Depositional conditions will also vary considerably between winter and summer. Consequently, the character of the tailings solids will be spatially heterogeneous.

Sampling programs for surficial soils are often based on the selection of sampling locations according to a systematic sampling grid (Black, 1965). Sampling based on a systematic grid involves the collection of samples at a relatively large number of regularly spaced sampling locations, and generally ensures representative sampling coverage. However, the large size of most tailings impoundments and the relatively high cost of collecting tailings solids samples from depth generally preclude the use of such systematic grids, and necessitate the judicious selection of sampling locations according to the anticipated conditions. Although the tailings are spatially heterogeneous, the variability is to some extent predictable if the history of tailings deposition is known. If this is the case, representative sampling locations can be selected relatively easily.

When the history of deposition at a tailings impoundment is not precisely known, a phased approach to an investigation may be desirable (ASCE, 1976). In the first stage, a number of widely spaced simple exploratory borings can be made in which 'disturbed' samples are obtained. Based upon the results of these borings, additional borings can be made between the initial borings to define the conditions in better detail. Samples in these additional borings could also be 'disturbed' or 'undisturbed', and could be taken continuously or at selected intervals. In general, sampling is most commonly performed at 0.75 or 1.5 m intervals of depth.

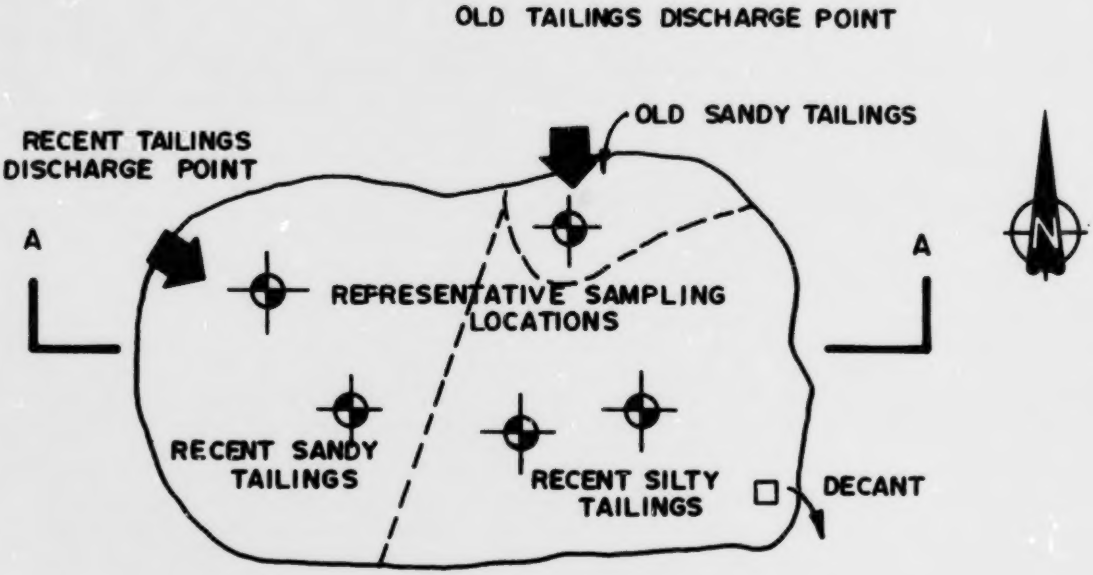
If soil conditions in a given area are well known and the stratification is simple with fairly thick individual strata of consistent physical properties, relatively widely spaced borings may be sufficient. If, however, soil conditions vary appreciably from place to place, more closely spaced borings could be required (ASCE, 1976). The number and spacing of boreholes must be determined by judgement as the work progresses. There should be a sufficient number to determine the stratification and interlayering of the various sized tailings solids. However, it should be emphasized that whereas relatively extensive investigation and testing might be appropriate where the subsurface conditions vary systematically, such extensive work may not be justified when the tailings vary erratically. In this situation, the investigation should concentrate on areas of the tailings impoundment which provide a conservative estimate of the item under investigation. This could include borings at each end of the basin but relatively few in-between.

Above all, it must be remembered that the validity of investigations carried out in laboratory tests rests solely on the quality of the samples and on how far they are representative of the stratum from which they are taken. An elaborate testing technique cannot compensate for the disturbance caused by sampling, transport and storage of the samples. Sampling technique and degree of sample disturbance are often questions of cost. The cost for a sample with a 125 mm diameter is in general three to four times higher than that for a 75 mm sample (Broms, 1980). Costs increase approximately with the square of the diameter. The quality of the samples must be related to the required accuracy of the results. In many cases, only a rough estimate is required of shear strength, compressibility or permeability and the maximum size of sample for tailings sampling is usually restricted to 75 mm.

An example of the selection of tailings sampling locations at a hypothetical tailings impoundment is illustrated in Fig. 4.1. Tailings were deposited at this impoundment in two stages, initially from the north side of the impoundment and subsequently from the west end. This discharge scheme resulted in deposition of recent sandy tailings at the west side, and old silty tailings underlying recent silty tailings at the east side. The old tailings and recent tailings may be different in character due to different ore grades, mill processes or weathering. The sandy tailings and silty tailings can differ considerably in physical and chemical character. Consequently, representative tailings sampling locations should be situated in each of these different areas to characterize the various types of tailings present in the impoundment.

Geostatistical methods such as those used in the mineral exploration and ore reserve estimation fields would, in most cases, be of limited application to investigations of tailings impoundments. The basic tool of geostatistical methods is the variogram. The variogram relates the distance between samples to a measure of the spatial variation in a specified parameter. The examination of variograms of, for example, metal content in an ore deposit as developed from the results of a preliminary exploration drilling program, may be useful in characterizing the variation or any directionality (anisotropy) in the variation of the metal content. Such information on the variation or directionality in the variation could be used to determine the drillhole spacings and patterns required to further detail the ore deposit most effectively. Details of the use of variograms in ore reserve estimation are provided by David (1977).

The use of variograms is of most benefit in situations where there is little prior knowledge or understanding of the factors controlling the spatial variability of a parameter. With regard to uranium tailings, there is generally a reasonable degree of prior knowledge so much of the information gained from the geostatistical methods may be already known. In addition, the development of appropriate variograms does require a considerable amount of data, which although relatively small in terms of an intensive mineral exploration program, may be substantial relative to a tailings investigation program.


OLD TAILINGS DISCHARGE POINT
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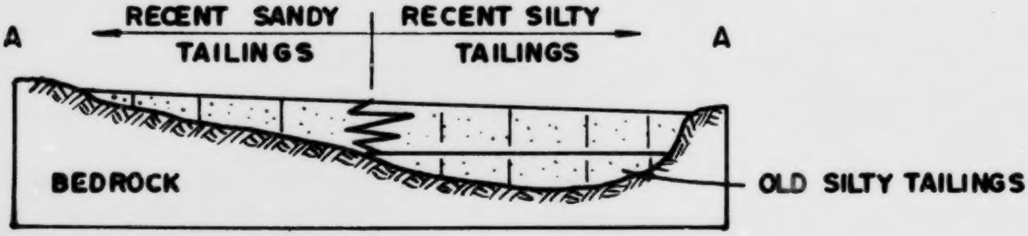
TAILINGS AREA - PLAN VIEW


A
RECENT SANDY TAILINGS
RECENT SILTY TAILINGS
A
BEDROCK
OLD SILTY TAILINGS

TAILINGS AREA-SECTION VIEW

Fig. 4.1 – Example of selection of sampling locations at a tailings impoundment

4.3 PHYSICAL CHARACTERIZATION

4.3.1 Parameters

A variety of parameters are important for the physical characterization of tailings solids. These parameters include: grain size, water content, density and shear strength and may be determined in situ or from tailings samples collected in the field and tested in the laboratory. Table 4.1 summarizes the parameters for physical characterization, the type of testing, and the importance of the various parameters.

As shown in Table 4.1, the grain size and water content of the tailings solids will influence a large number of factors within the tailings impoundment. Because of the importance of these parameters, a sampling program should characterize both the areal and vertical variations (tailings stratigraphy) of these parameters. Tailings grain size is readily determined from visual examination and laboratory tests on representative samples of tailings solids, and is normally included in most investigations of tailings impoundments. Parameters such as density and shear strength of the tailings solids are important for investigations which consider potential settlement or stability of the tailings.

In logging soils, the basic group to which they belong should be determined (e.g., sand, silt, etc.). Adjectives describing the tailings in greater detail such as, consistency, colour, odour, shape of grains where visible, and other factors should also be noted (ASCE, 1976; ASTM, 1983: D2488-69). Since tailings are hydraulically deposited in the tailings impoundments, stratification of the fine-grained and coarse-grained tailings often occurs. This stratification can significantly affect the permeability of a tailings deposit and should always be recorded, if present. Stratification is usually visible in undisturbed or split-spoon samples of coarse-grained materials (e.g., sands). In fine-grained soils (silts and clays) the outside of the sample may be smeared. In this case, portions of the samples should be split with a sharp knife and, if necessary, permitted to dry partially. Finally, it should be noted that a soil description should cover all soil components contained in the tailings. A driller may sense the presence of gravel, cobbles, boulders, or even rock through the action of the drilling tools, but such materials may not be recovered due to the small diameter of the sampler.

4.3.2 Sample Collection Methods

There is a wide variety of techniques available for the collection of tailings solids samples for the purpose of physical and chemical characterization. Although surface grab samples or shallow test pits are sometimes used in the qualitative investigation of surface layers in a tailings area, borings are the most commonly used method of investigating the subsurface conditions in a tailings area. In making borings, a hole is advanced by drilling. At intervals, the drilling is stopped and samples of the soil beneath the bottom of the drill hole are obtained by driving or pushing a suitable sampling device into the soil. Alternatively, continuous sampling may be used, with drilling only as necessary to ream the hole between sampling operations.

Sample collection methods generally comprise two basic categories: hand operated and drill rig operated. Hand operated methods are limited to sampling within a few metres of the tailings surface. Drill rig operated sampling methods are normally required for collection of tailings samples from greater depths.

For both hand operated and drill rig operated sampling methods, there are different methods available for the collection of different types of samples depending on the testing requirements. Thick-walled samplers will be suitable for obtaining 'disturbed' tailings samples for identification and index property tests and for determining the relative density of the tailings. However, tailings solids samples collected for the determination of physical parameters such as shear strength, and chemical parameters require relatively undisturbed samples which can be suitably preserved to avoid changes in the character of the sample. Only certain sample collection methods recover this type of sample. The various sample col-

Table 4.1 – Parameters for physical characterization of tailings solids

Parameter	Type of Test	Importance
Grain size	— Field examination — Laboratory	— Grain size of tailings will affect many factors in tailings areas such as hydraulic conductivity of the tailings, radon exhalation, wind-blown dust, chemical reactions.
Water Content	— Laboratory — In situ	— Water content of tailings will affect radon exhalation, wind-blown dust, oxygen penetration into tailings which is important to pyrite oxidation.
Density	— Laboratory — In situ	— In situ density will affect tailings settlement and stability.
Shear Strength	— Laboratory — In situ	— In situ shear strength will affect tailing stability.

lection methods together with their applications and limitations are described in Table 4.2. Details of these sample collection methods are found in the references noted in Table 4.2.

Hand operated tailings sampling methods are normally used where samples are required only from shallow depths, or the tailings impoundment is inaccessible to heavy machinery such as drill rigs. Of the

Table 4.2 – Tailings solids sampling techniques

Technique	Application	Limitations	Reference
Hand Operated (Shallow)			
1) Surface grab	— Preliminary examination or tailings surface surveys	— Samples will not represent deeper conditions due to effects of erosion, leaching, weathering.	
2) Hand augers	— Collection of samples for general characterization.	— Samples are highly disturbed and more difficult to preserve. Generally limited to above water table.	(1) (2)
3) Hand piston sampler	— Collection of samples for detailed characterization. Samples are less disturbed than auger samples. Samples can be retained in sampling tubes.	— Samples are relatively short in length, cannot be examined in the field if preserved in sampling tubes.	(1)
4) Thin-walled tube sampler	— Collection of samples for detailed physical and chemical testing. Samples retained and readily preserved in sampling tube. Long, continuous, relatively undisturbed samples can be obtained.	— Cannot be examined in the field if preserved in sampling tubes. — Generally limited to depths less than 5 m.	(3)
5) Gravity core sampler (Benthos, Alpine, Phleger)	— Collection of tailings samples which are submerged beneath surface water bodies.	— Cannot be examined in the field if preserved in sampling tubes. — Samples relatively short in length.	(4)
Drill Rig Operated (Deep)			
1) Split-spoon sampler	— Collection of samples for field characterization	— Samples relatively disturbed.	(1) (5)
2) Shelby tube sampler	— Collection of undisturbed samples for detailed physical and chemical testing. Samples retained in sampling tube and readily preserved.	— Samples are relatively short in length. (Typically 0.75 m). Only ends can be examined in the field if preserved in sampling tubes.	(1) (6)
3) Piston sampler	— Same as Shelby tube sampler but piston prevents any entry of tailings until proper sampling depth is reached.	— Samples are relatively short in length. (Typically 0.75 m). Only ends can be examined in the field if preserved in sampling tubes.	(1) (6)
4) Long thin-walled tube sampler	— Collection of long (up to 10 m), continuous, relatively undisturbed cores. Samples retained in sampling tubes. — Ideal for examination of tailings stratigraphy.	— Long cores are awkward to handle and transport. — Samples may not be sufficiently undisturbed for detailed physical testing.	(7)

References

1) Acker (1974)
2) ASTM Volume 04.08: D1452-80
3) Patterson et al. (1978)
4) Environment Canada (1983)
5) ASTM Volume 04.08: D1586-67
6) ASTM Volume 04.08: D1587-74
7) Personal Communication, Mr. J. Hayes, Site Investigations Limited, Peterborough, Ontario.

hand operated techniques shown in Table 4.2, hand piston samplers and thin-walled tube samplers are most applicable to detailed investigation of tailings impoundments. Hand operated piston samplers are similar to drill rig operated piston samplers and are discussed later in this section. Thin-walled tube sampling involves the advance of tubing (normally aluminum) using a hammer or drive weight. The tubing is advanced to the desired depth, sealed with a piston to retain the tailings in the tube and removed using a portable tripod and winch. The configuration of this equipment is shown in Fig. 4.2. Long thin-walled tube samples (as long as 3 m) can be cut to more manageable lengths in the field using pipe cutters.

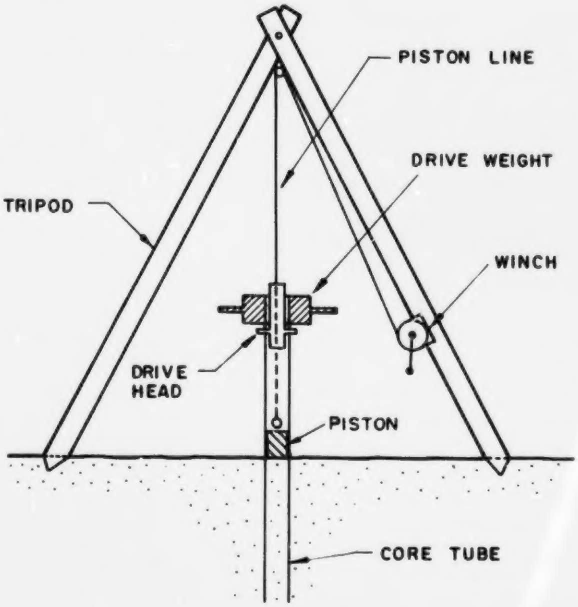


Fig. 4.2 – Manually operated thin-walled tube sampling equipment

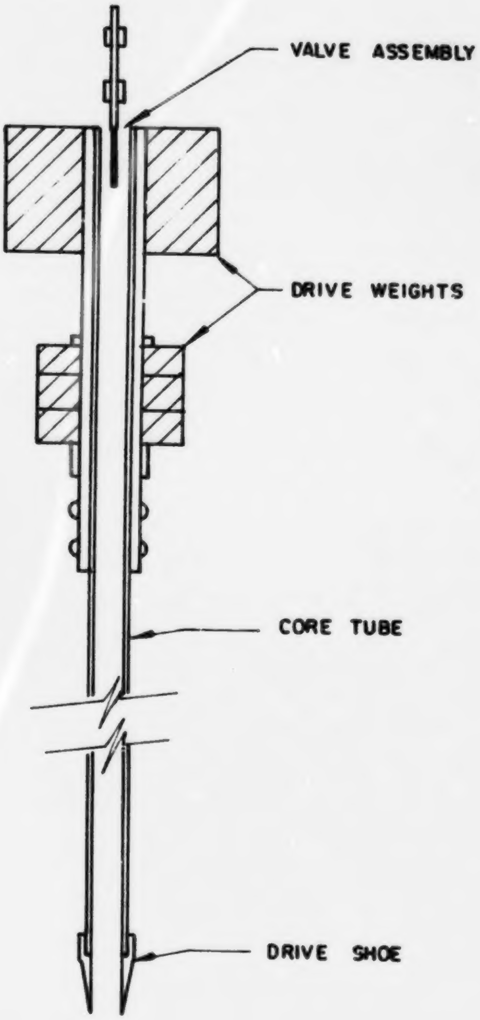


Fig. 4.3 – Benthos gravity core sampler for collection of submerged tailings samples

Manually operated gravity core samplers such as the Benthos, Alpine or Phleger samplers can be used to collect tailings core samples submerged beneath surface water bodies. These samplers are advanced into the tailings by their own weight and can be readily operated from a small boat or raft. A Benthos sampler is shown in Fig. 4.3.

Drill rig operated tailings sampling methods are used where samples are required from depths greater than several metres. Small diameter (7.5 to 10 cm O.D.) solid stem augers can be used above the water table if the tailings being sampled are not so loose or dry that they collapse into the borehole. Tailings sampling methods usually require a drill rig which can advance hollow drill string or casing, because boreholes extended below the water table do not stand open sufficiently to allow tailings sampling. This same consideration applies for the installation of piezometers in tailings. Hollow stem auger drilling or wash boring methods in which casing is advanced allow the use of the various tailings sampling techniques described in Table 4.2. These drilling methods and equipment are described by Acker (1974), and specific procedures for split-spoon, Shelby tube and piston sampling are described in ASTM (1983) Volume 04.08: Designations D1586-67 and D1587-74.

A split-spoon sampler is shown in Fig. 4.4. The sampler is a thick-walled sampler mounted on drill rods and extended down through hollow stem augers or drill casing to the desired depth in the tailings. The sampler is advanced by hammer into the tailings to collect the tailings sample (see Section 4.3.5) On recovery of the sampler, the tube of the split-spoon is split and the sample is removed. Split-spoon samples are relatively disturbed and cannot be adequately preserved when the tailings are chemically unstable. In addition, it is sometimes necessary to use a sample retainer in the shoe of the sampler to prevent the loss of the tailings samples.

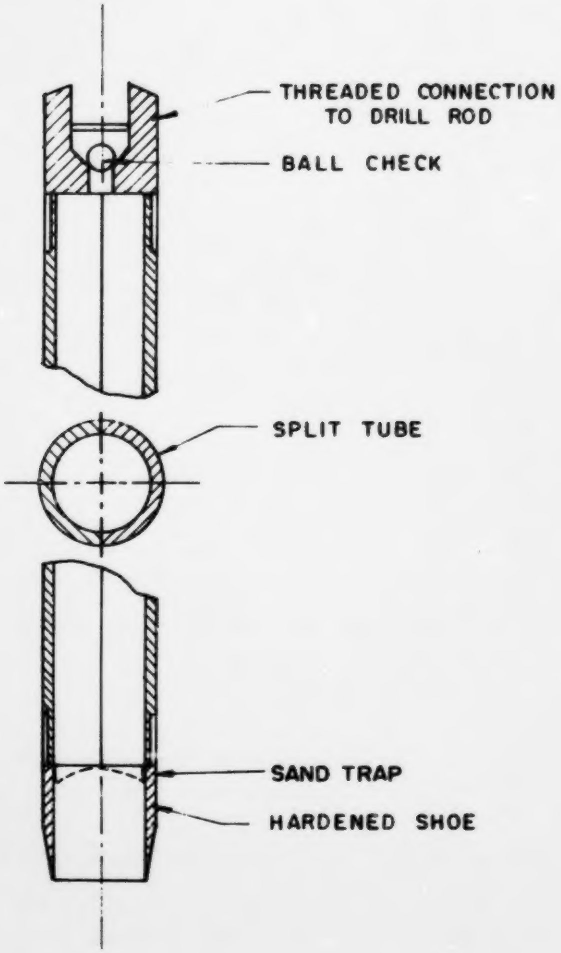


Fig. 4.4 – Details of split-spoon sampler (sand trap may be required for cohesionless tailings)

The operation of thin-walled Shelby tube and fixed piston samplers are shown in Fig. 4.5 and 4.6 respectively. These samplers are also operated on drill rods through hollow stem augers or drill casings but are normally advanced hydraulically or manually pushed into the tailings to minimize disturbance of the sample. Thin-walled samplers will only work in relatively soft or loose deposits and are not suitable for hard, dense or gravelly soil. However, taking good quality undisturbed samples in even soft tailings requires the use of a thin-walled sampler with proper clearance at the cutting edge. The sampler should have an area ratio, as defined by Hvorslev (1949), not exceeding 10 per cent. To meet this requirement, the wall thickness plus relief of the cutting edge of the sampler should not exceed 1.9 mm for a 76 mm diameter sampler (See Fig. 4.7). It is extremely important to note that the cutting edge of the sampler must be sharpened and not simply rolled in.

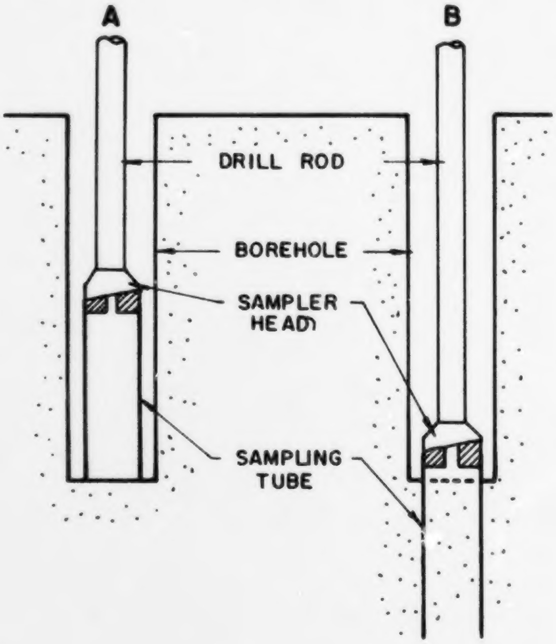


Fig. 4.5 – Operation of thin-walled Shelby tube sampler
A. Lowering of tube to bottom of borehole
B. Pushing of tube into formation

In the case of the piston sampler, the fixed piston prevents any material from entering the sampler as it is extended down through the augers or casing and helps minimize disturbance during sampling. For sampling, the piston remains stationary and the thin-walled barrel is advanced into the tailings. The tailings samples are retained within the Shelby tube and piston sampler tubes, although due to the usual cohesionless nature of tailings it may often be necessary to wait up to 15 minutes after the sampler has been advanced to allow the sample to set up within the sampling tube. In addition, extreme care is required not to jar the sampler while pulling it back up the hollow stem augers or casing. However, when recovered, such samples are relatively undisturbed

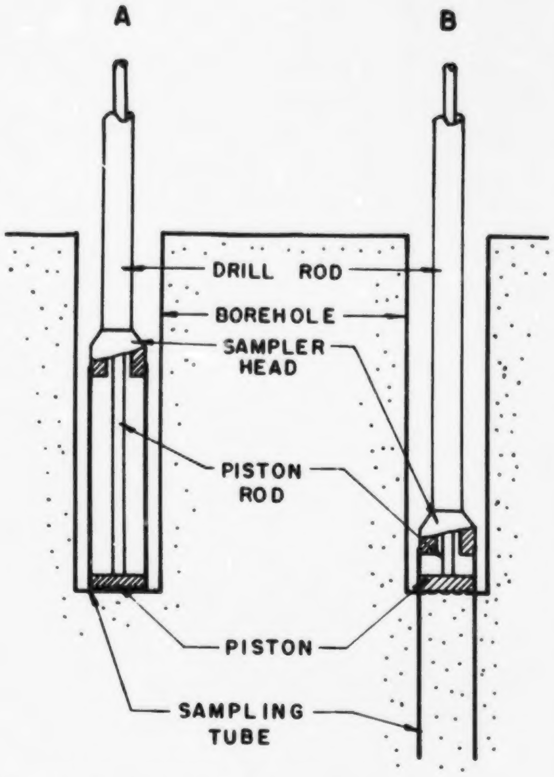


Fig. 4.6 – Operation of fixed piston thin-walled tube sampler
A. Lowering of tube to bottom of borehole. Piston prevents foreign material from entering sampling tube until sampler is activated
B. Pushing of tube into formation

and can be readily preserved. Sample handling and preservation are described in Section 4.3.3.

Hydraulic piston samplers (Osterberg samplers) have been used in Europe for sampling silts and clays but have not been widely used for tailings sampling, probably due to the difficulty in obtaining adequate hydraulic capacity on most drill rigs to properly activate the sampler.

Long thin-walled tube sampling using a drill rig is comparable to hand operated thin-walled tube sampling. This type of sampling is applicable when long continuous cores of tailings are required, such as for detailed examination of the tailings stratigraphy. Long thin-walled tube samples can be cut into more manageable lengths in the field using pipe cutters.

4.3.3 Sample Handling and Preservation Methods

Suitable handling and preservation methods are required for the collection of tailings solids samples in order to avoid changes in the character of the samples between the time the samples are collected and analysed. For physical testing of tailings solids samples, the primary concern is the prevention of moisture loss from the samples. Moisture loss from disturbed samples collected using hand augers or split-spoon samplers can be controlled by retention of the samples in plastic bags or preferably glass jars. Sample containers should be filled so as to exclude as much air as possible and should be tightly sealed.

Moisture loss from undisturbed samples which are retained in their original sampling tubes can be controlled effectively by sealing the samples into the sampling tubes using paraffin or epoxy sealants and caps. In situations where there is less than total sample recovery (i.e., the sampling tube is not completely filled), paraffin or epoxy sealants should be used to fill the empty portions of the tube in order to contain the sample with no air space.

In all cases, it is preferable to conduct detailed geotechnical analyses of the samples as soon as possible following collection to minimize possible changes in the character of the sample. Maximum recommended sample storage times for disturbed samples range from several days for plastic bags to several months for glass jars. Undisturbed samples in Shelby tubes should not be stored for longer than several weeks.

Because of the generally corrosive nature of tailings and tailings porewater, sampling tubes should have resistant plastic liners or be constructed of relatively resistant metals such as aluminum, coated steel or stainless steel. The selection of sampling tubes of a particular construction will depend on the sample collection method used and the physical and chemical nature of the tailings. Special considerations for the preservation of tailings solids samples for chemical analyses are discussed in Section 4.4.3.

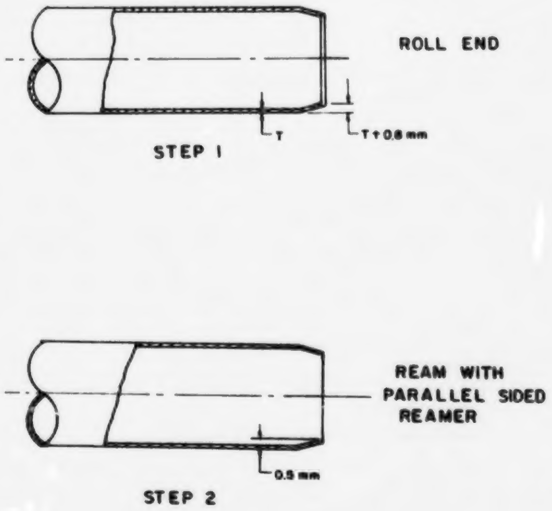


Fig. 4.7 – Details of thin-walled tube sampler cutting-edge

4.3.4 Laboratory Analytical Methods

Laboratory analysis of physical parameters such as grain size, water content, densities and shear strength of tailings solids can be conducted using standard testing methods used for natural soils. The grain-size distributions of the tailings solids are determined by sieve and hydrometer tests. Water contents are determined by weight loss on drying. Standard procedures for the preparation of soil or tailings samples for laboratory testing are described in ASTM (1983) Volume 04.08: D421-58 and D2217-66. Standard methods of laboratory testing of grain size, water content, density and shear strength are described in ASTM (1983) Volume 04.08: D422-63, D2216-80, D1557-78, and D3080-73 respectively. The drained or undrained shear strength of the tailings can be assessed by triaxial tests on carefully trimmed specimens of undisturbed samples. On loose tailings, sample disturbance can be a significant problem.

There are, however, special considerations for the laboratory testing of uranium tailings solids. The radioactivity of the tailings and emanation of radon gas from the tailings necessitates adequate dust control and ventilation in the testing laboratory to prevent ingestion or inhalation of radioactive materials. Tailings samples should also be handled using rubber gloves due to the chemically corrosive nature of tailings and tailings porewater.

4.3.5 In Situ Testing

Various in situ testing techniques are available for the determination of physical properties of tailings such as water content, density and shear strength. In concept, in situ testing of physical properties should be preferable to laboratory testing because the difficulties of sample disturbance during collection and handling are avoided. In reality, however, most in situ testing techniques have significant limitations which must be considered. The various in situ testing techniques are listed in Table 4.3. Details regarding these techniques are found in the references noted in Table 4.3.

The in situ water content of tailings can be determined using *nuclear moisture testing methods*. The configuration of typical nuclear moisture testing equipment is shown in Fig. 4.8. The nuclear moisture probe is normally operated inside a borehole cased with thin-walled aluminum, steel or plastic tubing. The operation of the probe is based on the detection of the degree of scattering and slowing of high energy neutrons emitted from a radioactive source in the probe. Water molecules are most effective in the moderation and capture of the emitted neutrons so that the resultant neutron radiation measured at the detector is inversely proportional to the water content of the tailings material surrounding the borehole.

Table 4.3 – Methods for in situ determination of physical parameters of tailings solids

Parameter	Test Method	Reference
1. Water Content	— Nuclear moisture probe	(1) (2)
2. Density	— Nuclear density probe	(2) (3)
	— Standard penetration test	(4) (5)
	— Cone penetrometer	(4) (6) (7)
3. Shear Strength	Common Methods:	
	— Standard penetration test	(6) (7)
	— Cone penetrometer	(6) (7)
	— Vane shear test	(8) (9)
	Specialized Methods:	
	— Pressuremeter	(6)
	— Borehole Shear	(6)
	— Plate bearing load	(6)
	— Field direct shear	

References

1) Keys and MacCarty (1971)
2) Black (1965)
3) Mittal and Morgenstern (1975)
4) Acker (1974)
5) ASTM Volume 04.08: D1586-67
6) Schmertman (1975)
7) ASTM Volume 04.08: D3441-79
8) Arman et al. (1975)
9) ASTM Volume 04.08: D2573-72

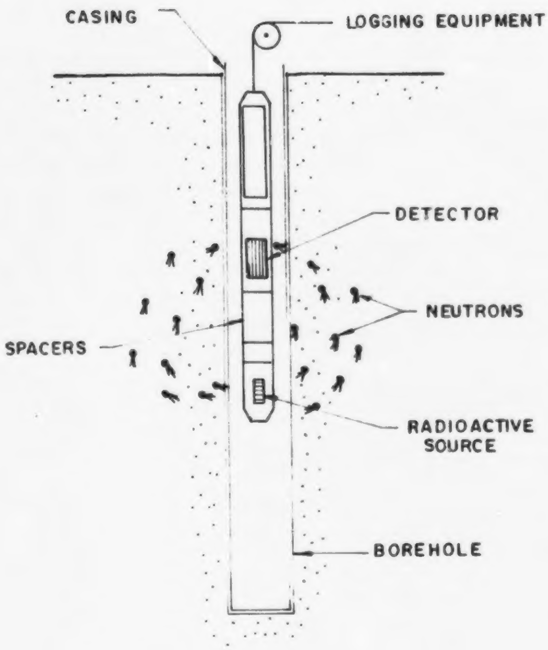


Fig. 4.8 – Typical configuration of in situ nuclear moisture testing equipment

There will also be some degree of neutron scattering due to the tailings solids. Large variations in tailings density such as are possible in tailings impoundments, may be reflected in apparent variations in the water content of the tailings. Consequently, nuclear moisture testing methods may not be suitable for the precise determination of water content in the tailings. Nuclear moisture testing methods are, however, highly suitable for monitoring relative temporal variations in water content because repeated measurements can be made at the same locations in boreholes.

Nuclear moisture testing equipment should be calibrated according to manufacturer's specifications for the particular borehole casing used and the tailings density.

Nuclear density testing methods are comparable to nuclear moisture testing methods. The configuration of typical nuclear density testing equipment is similar to that shown in Fig. 4.8 with a down-hole radioactive source and detector. The probe is operated inside a borehole cased with thin-walled aluminum, steel or plastic tubing. The operation of the probe is based on the detection of the degree of scattering of gamma radiation from the source by the tailings solids surrounding the borehole. Nuclear density testing methods have been used successfully in base metal mine tailings (Mittal and Morgenstern, 1975), but may be influenced by the higher ambient gamma radiation in uranium tailings.

Nuclear density testing equipment should be calibrated according to manufacturers' specifications for the particular borehole casing used and the ambient gamma radiation.

Standard penetration tests are performed during collection of tailings solids samples from boreholes using split-spoon sampling. Procedures for standard penetration tests are described in ASTM (1983) Volume 04.08: D1586-67. The test involves the advance of a 46 cm long, 5 cm diameter sampler into the tailings using a 63.5 kg hammer. The rate of advance is expressed as blows per specified incremental depth (generally 0.3 m), and reflects the relative density and shear strength of the tailings materials. Higher blow counts represent higher density and strength.

Experience and some test data indicate that either a 2.5 cm extra heavy pipe or an N rod can be used to depths of about 18 m (ASCE, 1976). Below this depth N rods should be used. Care should be taken to make joints up tight on the drill rod. Any lengths of rod having damaged couplings, or which are bent, should not be used. The drill hole in which penetration tests are to be made should not exceed about 9.0 cm in diameter. Larger drill holes significantly affect the results. The most common sources of error are inadequately cleaning the boring of all loose material; allowing the base of the borehole to become disturbed if the water level in the borehole is significantly below that of the water level in the surrounding tailings; not maintaining the sampler shoe properly sharpened; and not dropping the sampling hammer freely through the required distance for a full square blow. Usually, the hammer is hoisted by a rope over a cathead and dropped by slacking the rope. Two turns of the rope on the cathead is considered the maximum allowable but one turn is considered preferable to obtain a free fall. Wire lines attached to the hoisting drum should not be used since it is difficult to obtain a free fall.

Cone penetration testing is comparable to standard penetration testing but involves the advance of a cone-shaped probe while recording blows per incremental advance or actually measuring penetration resistance using a load transducer. Procedures for cone penetration testing are described in ASTM (1983) Volume 04.08: D3441-79. Cone penetration has increased in popularity in recent years (Wilson and Ohya, 1981). The most commonly used cone test is the Dutch cone test. The resistance to penetration is the sum of point resistance and frictional resistance on the sides of the shaft. The more sophisticated systems can differentiate between the point and frictional components of the resistance, and the ratio between frictional and point resistance (Friction Ratio) is one aid in differentiating between various soil types. Clean sands generally exhibit very low ratios (low friction component in comparison to point resistance), while an increase in clay content will usually result in a higher ratio, more often the result of a reduction in point resistance rather than an increase in the frictional component (NAVFAC, 1982).

Although the speed of operation of static cone tests allows considerable data to be obtained in a relatively short period of time, it should be noted that a major drawback is that samples are not recovered for logging and identification. Cone tests should not therefore be used in isolation but in combination with borings where they can be used to supplement the existing borehole data. Sampled borings adjacent to the cone penetration tests can be used to calibrate the cone penetration response for further testing. Cone penetration tests are discussed in detail by Sangerlat (1972), and in FHA (1977).

Vane shear testing is used for the determination of the in situ shear strength of soft fine-grained tailings (slimes), and involves the insertion and rotation of a 4-bladed vane in the tailings. The resistance to rotation of the vane is related to the shear strength of the tailings. Vane testing can be conducted at different depths down a borehole casing or drill string during drilling. The configuration of vane shear testing equipment is shown in Fig. 4.9. Procedures for vane shear testing are described in ASTM (1983) Volume 04.08: D2573-72. Vane tests should not be performed if sand layers, gravel, roots or other organic materials are believed to be present.

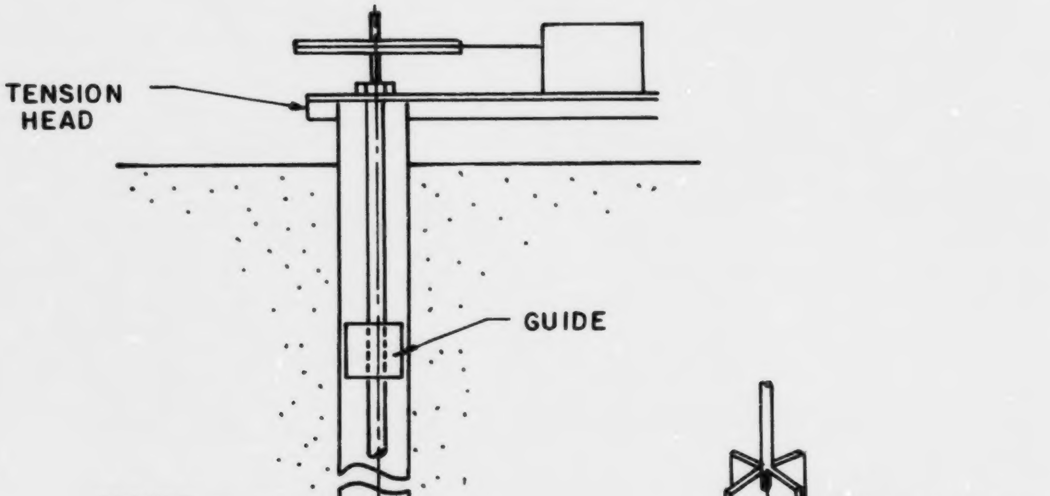


Fig. 4.9 – Vane testing equipment for determination of in situ shear strength

Pressuremeter testing is also sometimes used for the determination of in situ shear strength or the stress-strain properties of tailings, and involves the expansion of an elastic pressuremeter cell in a borehole while recording changes in the cell volume with increasing cell pressure. The relationship between the cell volume change and cell pressure is related to the shear strength of the tailings materials. Pressuremeters have not been widely used in tailings investigations although the new self-boring pressuremeters (Baguelin & Jezequel, 1980 and Wroth, 1980) which drill their own way through the soft soil beneath them may be able to produce very high quality test data. However, again no actual soil samples are obtained.

Borehole shear, plate bearing and *field direct shear tests* are specialized techniques that are not commonly used to determine the in situ shear strength of tailings.

4.4 CHEMICAL/MINERALOGICAL CHARACTERIZATION

4.4.1 Parameters

Laboratory testing for the chemical and mineralogical characterization of tailings solids can be categorized into two basic types:

1) Chemical analysis – to determine the bulk chemical properties of the tailings solids and infer the mineralogy;
2) Mineralogical identification and analysis – to determine the minerals present in the tailings and the chemical composition of the minerals.

The analyses for the chemical and mineralogical characterization of tailings solids are listed in Table 4.4.

The *acid generation potential* and the *acid neutralization potential* are important parameters for the assessment of acid generation in tailings impoundments. The acid generation potential of tailings is a function of the sulfide mineral content. The oxidation of sulfide minerals (commonly pyrite) in the tailings can result in the production of sulfuric acid. The ability of the tailings solids to neutralize the effect of acid production, or the acid neutralization capacity, is a function of the concentration of acid consuming minerals such as carbonates, oxyhydroxidos, aluminosilicates and chemicals added to the tailings.

The *cation exchange capacity* of the tailings indicates the overall ability of the tailings solids to adsorb cations from the tailings porewater. Generally, constituents such as heavy metals and various radionuclides are preferentially adsorbed on geologic materials, and consequently the cation exchange capacity can be important to the mobility of these constituents in tailings impoundments. The analysis of constituents which are water and acid leachable from the tailings solids can indicate those constituents which may be mobilized in the tailings impoundment by the infiltration of precipitation into the tailings or the movement of acid water from pyrite oxidation through the tailings. Total elemental analyses of the tailings solids can be used to infer the bulk mineralogy of the tailings.

A variety of techniques is used for mineralogical identification and analysis of the tailings. X-ray diffractometry and ore microscopy are used to identify the minerals present in the tailings. Techniques such as SEM-energy dispersive X-ray fluorescence and Quantimet analysis are used to identify the minerals present and determine their respective chemical compositions.

Table 4.4 – Analyses for chemical / mineralogical characterization of tailings solids

Chemical Analysis
Acid Generation Potential (sulfide mineral content)
Acid Neutralization Potential
Cation Exchange Capacity
Water Leachable Constituents (i.e., sulfate)
Acid Leachable Constituents (i.e., iron, manganese, carbonate)
Total Elemental Analysis
Mineralogical Identification and Analysis
X-ray Diffractometry
Ore Microscopy
SEM-Energy Dispersive X-ray Fluorescence
Quantimet Analysis

4.4.2 Sample Collection Methods

The collection of tailings solids samples for chemical and mineralogical characterization is generally conducted in conjunction with the collection of samples for physical characterization. The possible sample collection methods discussed in Section 4.3.2 are also applicable to chemical sampling depending on the chemical and mineralogical nature of the tailings and tailings porewater. In most cases, for the collection of tailings solids samples for chemical analyses, it is necessary to use Shelby tube or thin-walled tube sampling methods to recover relatively undisturbed samples which can be effectively sealed to prevent moisture loss and exposure to the atmosphere.

The loss of moisture from tailings solids samples can result in the precipitation of mineral phases from the tailings porewater and significant changes in the chemical and mineralogical composition of the tailings solids. Tailings solids samples which contain significant concentrations of sulfide minerals or ferrous iron in the porewater can undergo significant oxidation when exposed to the atmosphere during sampling and storage. The oxidation of sulfide minerals or ferrous iron in the tailings samples will result in the generation of acid in the tailings solids samples which can significantly alter the chemical and mineralogical composition of the tailings.

4.4.3 Sample Handling and Preservation Methods

As discussed in the preceding section, tailings solids samples for chemical and mineralogical analyses are generally collected using methods which enable the retention of the samples directly in the sampling tubes. In order to prevent moisture loss and exposure to the atmosphere, the tailings samples are sealed into the sampling tubes using plastic caps or rubber plugs sealed with paraffin wax or epoxy. The samples should be stored at 4°C to inhibit chemical reactions in the samples. Samples which are anticipated to be highly chemically unstable or which need to be stored for long periods of time before analysis can be frozen. Freezing may, however, affect physical parameters such as shear strength. The tailings solids samples should remain sealed and appropriately stored until analyses are performed. In all cases it is preferable to conduct analyses as soon as possible to minimize storage times and the possibility of chemical changes.

4.4.4 Laboratory Analytical Methods

The chemical and mineralogical analysis of uranium tailings solids can generally be conducted using standard analytical methods for soils and rocks. These methods are described by Black (1965), Donaldson (1980) and Johnson and Maxwell (1981). Analysis for the determination of acid producing potential is described by Duncan (1972).

4.5 RADIOLOGICAL CHARACTERIZATION

4.5.1 Parameters

Members of the uranium-238 radioactive decay series will be present in the tailings. The decay chain headed by uranium-235 will also be present but in environmentally insignificant quantities because of its low abundance (0.7%) in natural uranium. Also, natural thorium (thorium-232) and its decay products may be present in amounts depending on the mineralogy of the ore mined. The uranium-238 and thorium-232 decay chains are shown in Appendix A.

The radionuclides in these decay chains do not all have the same potential environmental effects. Their specific activity in tailings material, half-lives, mode and energy of radioactive decay, and their mobility through the environment are a few of the many factors that affect their potential impact. Table 4.5 lists the major radionuclides that should be measured in assessing the radiological characteristics of tailings solids. Because of the insensitivity and general inaccuracy of gross radioactivity measurements (gross alpha or beta) of collected samples, such measurements are not recommended for the radiological characterization of tailings solids other than perhaps as a screening technique.

4.5.2 In Situ Testing

The major techniques used for the in situ determination of the radiological character of uranium tailings are surface radiation surveys and subsurface gamma probes.

Surface radiation surveys are carried out using portable beta/gamma sensitive radiation meters that incorporate either a scintillation or ionization tube detector. The response of the meter is measured either in counts per minute, or Gray (Gy) or Coulomb per kilogram (C/kg) per hour. Typically, the meter is held approximately 1 m from the ground and the area to be surveyed is traversed on a grid. Background measurements at locations away from known sources of contamination are also recorded for purposes of comparison. The survey instruments usually respond to the total ambient radiation field but instruments capable of energy discrimination are available that respond only to radiation from the natural uranium chain or thorium chain or potassium (potassium-40) radionuclides.

Subsurface gamma surveys involve lowering a gamma detector down a borehole and recording the gamma field at various depths. This is done either manually or automatically with a motor-driven raising and lowering device and a chart recorder. This technique is valuable in determining the vertical variability of radioactive constituents in the tailings.

4.5.3 Sample Collection Methods

Sample collection methods are generally similar to the methods used in collecting samples for chemical

Table 4.5 – Parameters for radiological characterization of tailings solids

	Parameter
	Gross gamma
Uranium Decay Series	Natural uranium Thorium-230 Radium-226 Lead-210 Polonium-210
Thorium Decay Series	Thorium-232 (natural thorium) *Radium-228 *Thorium-228 *Radium-224

*Not generally important unless significant concentrations of thorium-232 are present in the tailings.

analyses (see Section 4.3.2). As usual, the samples should be selected to be as representative as possible of the area under study. While gross sample sizes of 100 to 200 g are sufficient for complete radionuclide analyses, it may be desirable to collect larger samples which could be split for archival or quality control purposes. It is often very important to know the grain-size distribution of the radionuclides on the surface tailings material. This is because the inhalation of suspended uranium tailings particulate matter can be an important radiation exposure pathway and specific radioactivity (radioactivity per unit mass) is highly dependent on particle size. Measurements on Elliot Lake tailings taken from the Elliot Lake Environmental Assessment (James F. MacLaren Ltd., 1978) are shown in Table 4.6 and indicate that specific activity tends to be highest in the smallest particle size range (<38 μm). For these reasons, sufficient surface material should be collected to enable representative radionuclide determinations in each of the selected particle size ranges.

4.5.4 Sample Handling and Preservation Methods

Sample handling and preservation methods are identical to those used for chemical characterization (see Section 4.3.3). The containers should be suitably identified to indicate their radioactive nature.

Of the radionuclides shown in Table 4.5, polonium-210 has the shortest half-life of 138 days. Unless lead-210 and polonium-210 are assumed to be in secular equilibrium, the time between sample collection and analysis should be kept as short as possible, preferably less than 30 days. A correction for the decay of polonium-210 can be calculated if sampling and analysis dates and lead-210 concentrations (the grandparent of polonium-210) are known. However, a lengthy sampling-analysis delay greatly reduces the accuracy of this correction.

It is also important to keep tailings samples tightly sealed in their containers or sampling tubes to prevent the loss of radon gas and the consequent loss of radon daughters from the samples.

4.5.5 Laboratory Analytical Methods

Radionuclide analyses generally involve chemical separations followed by the counting of radiations (alpha, beta or gamma) specific to the radionuclide being analysed using energy discriminating counting systems. Details of standard techniques may be found in Smithson et al. (1978). (Note: A revised manual on the techniques for radionuclide analyses is being prepared, under contract with NUTP, and will be available in 1985.)

4.6 QUALITY ASSURANCE FOR SOLIDS SAMPLING

A soil sample may be disturbed at any time between the point of sampling and the time at which it is extruded (ASCE, 1976). Some of the more important areas of concern are:

1) *During drilling of the borehole*
   - Inadequate clearing of the borehole. The depth to which the borehole is cleaned should be regularly checked with a sounding tape;
   - Failure to maintain sufficient hydrostatic head within the boring. In sands the water level in the borehole should, if at all possible, be maintained above the piezometric level of the formation being sampled, or the soil at the bottom of the borehole may be loosened;
   - Using too large a pump which could loosen the soil at the base of the borehole.
2) *During sampling*
   - Excessively thick-walled samplers;
   - Excessive vibration.
3) *During recovery of the sample*
   - Undisturbed samples should not be jarred or tapped.
4) *During transport of the samples to the laboratory*
   - Samples for detailed geotechnical testing should not be allowed to freeze;

Table 4.6 – Tailings radionuclide analysis by size class

Results given as Bq/g except where noted

			Tyler Sieve Series				
			70	100	140	200	400
		Particle Size (µm)					
Location	Radioisotope	>212	150-212	106-150	75-106	38-75	<38
Stanrock (Inactive)	Lead-210	—	—	—	—	—	16.5
	Polonium-210	—	—	—	—	—	7.8
	Radium-226	0.67	1.7	0.67	3.6	1.0	8.15
	Radium-228	—	—	—	—	—	2.0
	Thorium-228	0.056	0.18	0.32	2.6	0.85	1.7
	Thorium-230	0.11	0.48	0.70	0.44	0.70	1.8
	Thorium-232	0.026	0.085	0.21	0.21	0.70	0.41
	Uranium-234	—	0.18	—	2.6	—	0.70
	Uranium-235	—	—	—	—	—	0.008
	Uranium-238	—	—	—	—	—	0.21
	Uranium ('Natural'– measured as µg/g)	5	9	10	13	15	—
Nordic (Inactive)	Lead-210	—	—	—	—	—	8.90
	Polonium-210	—	—	—	—	—	2.6
	Radium-226	3.7	2.0	1.3	0.37	0.52	20.5
	Radium-228	—	—	—	—	—	—
	Thorium-228	0.22	0.12	0.21	0.070	0.33	0.67
	Thorium-230	1.1	0.59	0.89	0.31	1.3	1.5
	Thorium-232	0.096	0.044	0.096	0.041	0.17	0.15
	Uranium-234	—	—	—	—	—	0.67
	Uranium-235	—	—	—	—	—	0.008
	Uranium-238	—	—	—	—	—	0.18
	Uranium ('Natural'– measured as µg/g)	11	9	11	12	13	—
Long Lake (Active)	Lead-210	—	—	—	—	—	—
	Polonium-210	—	—	—	—	—	—
	Radium-226	2.1	1.9	0.89	0.37	6.70	2.3
	Radium-228	—	—	—	—	—	3.7
	Thorium-228	0.089	0.16	0.10	0.31	0.37	0.96
	Thorium-230	0.63	0.48	0.67	1.6	1.1	5.6
	Thorium-232	0.085	0.067	0.096	0.26	0.37	0.93
	Uranium-234	0.41	—	—	—	—	—
	Uranium-235	0.012	—	—	—	—	—
	Uranium-238	0.30	—	—	—	—	—
	Uranium ('Natural'– measured as µg/g)	—	22	38	21	52	87
Quirke (Active)	Lead-210	—	—	—	—	—	—
	Polonium-210	—	—	—	—	—	—
	Radium-226	1.0	9.25	0.52	6.70	1.1	35.0
	Radium-228	—	—	—	—	—	—
	Thorium-228	0.16	0.093	0.19	0.48	0.26	1.1
	Thorium-230	1.4	0.59	1.7	3.0	1.9	10.5
	Thorium-232	0.11	0.078	0.13	0.37	0.23	1.1
	Uranium-234	0.29	—	—	—	—	—
	Uranium-235	0.010	—	—	—	—	—
	Uranium-238	0.21	—	—	—	—	—
	Uranium ('Natural'– measured as µg/g)	—	60	48	35	52	113

Note
Analysis not undertaken for items marked '—'.

Reproduction of Table 3.7, Volume II of Elliot Lake Environmental Assessment by James F. MacLaren (1978).

- Undisturbed samples should be carefully transported in wooden crates separated by polystyrene, wood chips or the like.

Of the above factors, those related to drilling of the borehole are the most critical. It is essential that the engineer, hydrogeologist and/or engineering technician supervising the borehole be aware at all times of the depth to the base of the drill-string, the water level inside and probable water level outside the borehole, and the depth to which the borehole is open. Any water level changes during drilling must also be recorded.

The accurate and comprehensive recording of field observations and field data is a vital component of tailings solids sampling programs. Field data from a tailings solids sampling program will include the sample locations and depths, sample type, sampling methods, sample character, and field measurements. Field data such as these from a drilling program are best recorded on prepared borehole log forms to ensure that all pertinent observations are made and the information is recorded in a standard manner. An example of a field borehole log form is shown in Fig. 4.10.

The radiological characterization of the tailings involves both in situ field measurements and laboratory analyses, each of which requires quality assurance programs.

The portable radiation survey instruments used for the in situ testing must give readings that refer to standard units. Thus, prior to use, each instrument should be calibrated with a known reference source. For the gamma/beta instruments, this involves measuring exposure rates at certain fixed distances from the source. Allowance is made for source decay and the exposure rates at each distance are calculated. Instrument calibration potentiometers are then adjusted to indicate the computed exposure rates at the specified distances. Alternatively, if the instrument uses other measurement units (e.g., counts/s), the measured values are noted. All instruments should be calibrated if possible near the centre of the meter scale on each exposure range.

A common gamma calibration source is radium-226. Standard tailings samples can also be used. Calibration of beta measuring instruments can be performed with a Technetium-99 source.

Following the initial calibration, the instruments should be checked daily at a reference distance from the calibration sources. Battery checks of the self-powered instruments should be made before any series of measurements are to be carried out.

Quality assurance for the laboratory radionuclide analyses involves the calibration of the complete counting system using reference source materials designated by the U.S. Nuclear Regulatory Commission or National Bureau of Standards. Basically, the entire measurement procedure from chemical separation to sample counting, is performed using reference sources specific to the radionuclide being analysed. Details of the techniques used are referenced in Smithson et al. (1978) (see Section 4.5.5).

4.7 PROGRAM COSTS

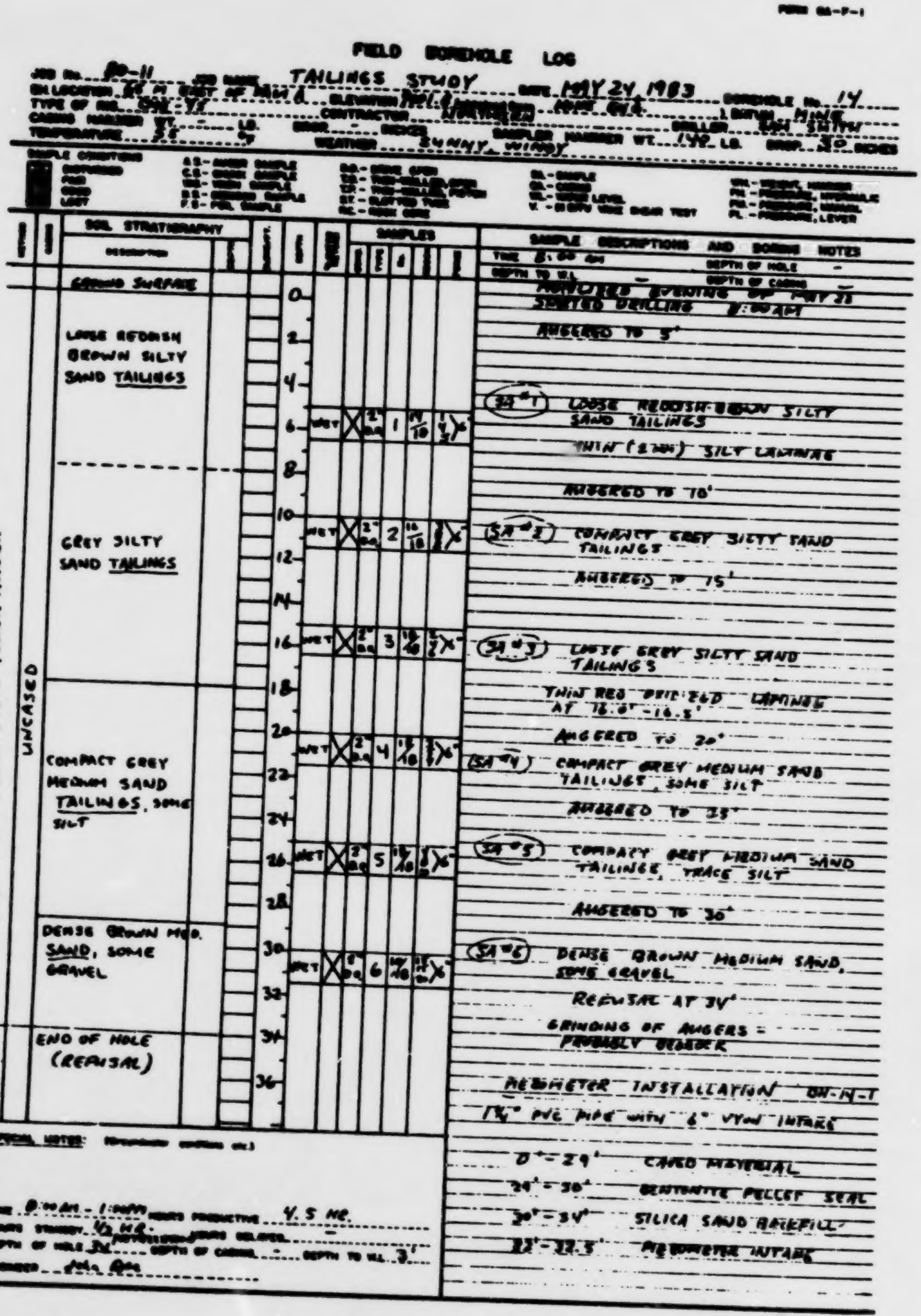
The cost of a tailings solids sampling program will depend on the intensity of the program as reflected by the number of sampling locations and individual samples; the depth from which samples are recovered; and the actual sampling methods used. The following are general unit cost estimates for several of the key solids sampling and testing procedures, which can be used to develop estimates for overall program costs.

Manual sampling of the tailings solids using thin-walled tube methods for the collection of continuous cores from shallow depth requires two field persons and typically yields approximately 1 to 2 metres of tailings core per hour.

Drill rig operated sampling methods for the recovery of tailings solids samples with split-spoon, Shelby tube or piston samplers can advance at rates of 2 to 4 metres per hour for split-spoon sampling at 1.5 metre depth intervals, but at only 1 to 2 metres per hour when continuous sampling or Shelby piston samples are required. Drill rig operated methods require a driller, driller's helper and drilling/sampling supervisor. Typical hourly rates for a drill rig with driller and helper range from $75 to $100 per hour in 1984.

In situ testing such as cone penetration tests and vane shear tests also require a drill rig. Cone penetration test rates are typically 5 to 10 metres per hour. Vane shear tests require 15 to 30 minutes per test.

Manual and drill rig sampling methods, and in situ testing methods generally require experienced specialist field personnel to supervise the field operations, accurately record field observations and measurements, and properly recover and preserve the samples. Typical consultants' rates for such specialist personnel range from $25 to $35 per hour for technicians, from $35 to $50 per hour for engineers/hydrogeologists in 1984.



FORM [illegible]

FIELD BOREHOLE LOG

JOB No. 80-11 JOB NAME TAILINGS STUDY DATE MAY 24 1983

BH LOCATION 55 m EAST OF [illegible] ELEVATION [illegible] BOREHOLE No. 14

TYPE OF RIG [illegible] CONTRACTOR [illegible] DATUM MINE

CASING HAMMER WT. - LB. DROP - INCHES DRILLER SAM SMITH

TEMPERATURE 55 °F WEATHER SUNNY, WINDY SAMPLER HAMMER WT. 140 LB. DROP 30 INCHES

SAMPLE CONDITION

SOIL STRATIGRAPHY

GROUND SURFACE

0

2 LOOSE REDDISH BROWN SILTY SAND TAILINGS

4

6 WET 2" DO 1

8

10

12 GREY SILTY SAND TAILINGS

14

16 WET 2" DO 3

18

20 WET 2" DO 4

22 COMPACT GREY MEDIUM SAND TAILINGS, SOME SILT

24

26 WET 2" DO 5

28

30 DENSE BROWN MED. SAND, SOME GRAVEL

32 WET 2" DO 6

34 END OF HOLE (REFUSAL)

36

3¼" I.D. HOLLOW STEM POWER AUGER

UNCASED

SAMPLE DESCRIPTIONS AND BORING NOTES

TIME 8:00 AM DEPTH OF HOLE -

DEPTH TO W.L. - DEPTH OF CASING -

MOBILIZED EVENING OF MAY 23

STARTED DRILLING 8:00 AM

AUGERED TO 5'

SA #1 LOOSE REDDISH-BROWN SILTY SAND TAILINGS

THIN (2 mm) SILT LAMINAE

AUGERED TO 10'

SA #2 COMPACT GREY SILTY SAND TAILINGS

AUGERED TO 15'

SA #3 LOOSE GREY SILTY SAND TAILINGS

THIN RED OXIDIZED LAMINAE AT 16.0' - 16.5'

AUGERED TO 20'

SA #4 COMPACT GREY MEDIUM SAND TAILINGS, SOME SILT

AUGERED TO 25'

SA #5 COMPACT GREY MEDIUM SAND TAILINGS, TRACE SILT

AUGERED TO 30'

SA #6 DENSE BROWN MEDIUM SAND, SOME GRAVEL

REFUSAL AT 34'

GRINDING OF AUGERS = PROBABLY BEDROCK

PIEZOMETER INSTALLATION BH-14-1

1½" PVC PIPE WITH 6" VYON INTAKE

0' - 29' CAVED MATERIAL

29' - 30' BENTONITE PELLET SEAL

30' - 34' SILICA SAND BACKFILL

33' - 33.5' PIEZOMETER INTAKE

SPECIAL NOTES: (Groundwater conditions etc.)

TIME 8:00 AM - 1:00 PM HOURS PRODUCTIVE 4.5 HR.

HOURS STANDBY ½ HR. HOURS DELAYED -

DEPTH OF HOLE 34 DEPTH OF CASING - DEPTH TO W.L. 3'

ENGINEER John Doe

Golder Associates

JOB No. 80-11

BOREHOLE No. 14

DEPTH 0 TO 34'

Fig. 4.10 – Example of field borehole log (completed for a typical tailings boring)

4.8 REFERENCES

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D1586-67	Method for penetration test and split-barrel sampling of soils.
D1587-74	Method for thin-walled tube sampling of soils.
D2216-80	Method for laboratory determination of water (moisture) content of soil, rock and soil-aggregate mixtures.
D2217-66	Method for wet preparation of soil samples for particle-size analysis and determination of soil constants.
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5. SURFACE WATER AND SEEPAGE

5.1 OBJECTIVES

The migration of chemical or radioactive constituents out of a uranium tailings impoundment in surface water runoff or localized seepage can have an important impact on surrounding lakes and streams. Therefore, the objective of a surface water and seepage sampling program at a tailings impoundment is to characterize the quantity and quality of surface water flow and seepage from the tailings impoundment in order to assess potential environmental impact.

Surface water runoff refers to water that exits a tailings impoundment by surface water flow. This runoff can be derived from precipitation, from surface water that originates outside an impoundment or from tailings porewater which discharges to surface water inside the tailings impoundment. Seepage refers to porewater which emerges from the ground and discharges into surface water in the immediate (within tens of metres) vicinity of a tailings impoundment. This differs from porewater which exfiltrates from the tailings into the groundwater system and is not immediately discharged to surface water.

Characterization of runoff and seepage is also important in the calculation of an overall hydrologic budget for a tailings impoundment. The hydrologic budget can be used to estimate the amount of precipitation that infiltrates the tailings, and consequently the amount that exfiltrates from the tailings into the groundwater system.

5.2 SELECTION OF SAMPLING LOCATIONS

For the purpose of assessing the potential impact of surface water runoff on the surrounding environment, sampling locations are normally situated where surface water collects on, or exits from, a tailings impoundment. At such locations, measurements of runoff quantity and quality can be made to estimate loadings to surface water bodies surrounding the tailings impoundment. To develop a hydrologic budget for a tailings impoundment, sampling locations should also be situated where surface water flows enter the tailings impoundment, and at selected locations where surface water collects or travels across the tailings impoundment. At such locations, measurements of surface water quantity and quality can be made to determine changes in quantity or quality as the surface water travels across the tailings impoundment.

Locations for sampling of seepage from a tailings impoundment are established where the seepage is observed to emerge. Seepages can be diffuse sources such as a series of emergent flows distributed along the toe of a dam, or can be highly localized such as one that emerges from a fissure in bedrock. Regardless of the nature of the seepage, it is preferable to situate sampling locations as near to the point of emergence as possible so that representative quantities and qualities can be measured and soil adsorption be minimized.

5.3 SURFACE WATER

5.3.1 Flow Measurements

Surface flows in and around tailings impoundments may include streams, channels, ditches and pond outfalls. In all instances, the basic technique used to estimate flow is to develop a 'rating curve' at each specific location which correlates the depth of flow and flow rate from repeated measurements of both water depth and flow over a wide range of flows. Depth readings are made using a staff gauge, float, pressure or electronic sensor. Flow measurements are normally made using current velocity meter-stream area calculations for the development of rating curves. Procedures for this method of stream flow measurement are described in ASTM (1983) Volume 11.01: D3858-79. Velocity-area methods can also be used for periodic point measurements.

Staff gauges are relatively inexpensive and require little in the way of maintenance. When a staff gauge is used, flowrates are only known for those times when the gauge is visited and the depth read. To obtain more frequent or continuous measurements of flow, float, pressure or electronic depth measuring devices can be connected to automatic recorders. Recorders are more expensive but the information they provide can be used to better understand flow behaviour and they do not require frequent attention.

Regardless of whether manual or automatic depth reading methods are used, the location of a flow measuring station must be such that backwater effects or other conditions that can induce errors into measurement are avoided.

The surface water flow that leaves a tailings impoundment area typically is discharged via a collection pond. Such outflows can be measured using weirs or flumes. V-notch or rectangular weirs are the more commonly used method due to the relatively higher costs of flumes and the difficulties in installing flumes correctly. An example of a small V-notch weir is shown in Fig. 5.1. V-notch weirs are more suited to measuring relatively low flow rates (less than 0.3 m^3/s or 10 cfs) but may be more susceptible to clogging by floating debris. The flows through weirs and flumes are also derived by measuring water depth and using a rating curve for the specific type of installation. Either manual or automatic depth recording can be used. Flow measurement techniques are described in detail in ASTM Volume 11.01: D2034-68, and D1941-67.

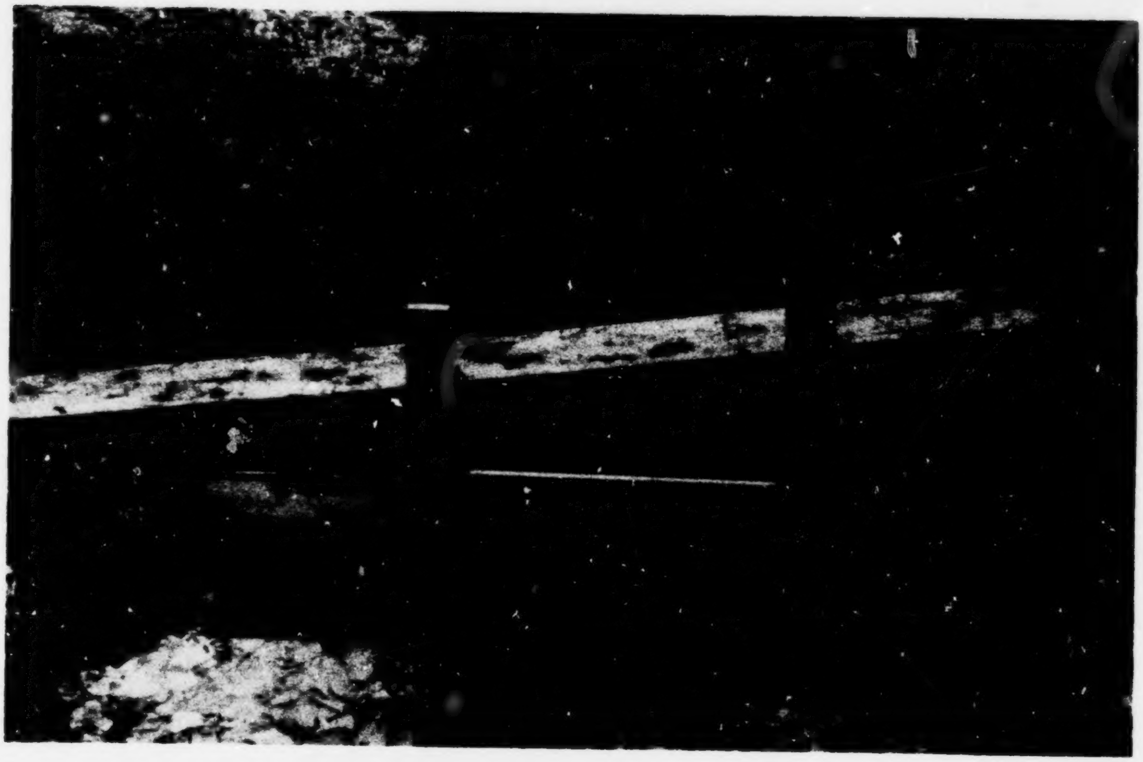


Fig. 5.1 – Example of a small V-notch weir of plywood construction

5.3.2 Chemical Sampling

5.3.2.1 Parameters

A wide variety of chemical and radiological parameters may be potentially important for the sampling of surface water runoff from a tailings impoundment. Key parameters for water sampling are shown in Table 5.1 and include various indicator parameters such as pH, electrical conductance (EC) and total dissolved solids (TDS), major ions, trace metals, and radionuclides. For a given tailings impoundment, this list can serve the basis for the selection of appropriate sampling parameters, but parameters could be added or deleted according to site-specific considerations such as the chemical composition of the tailings solids and mill effluent, or requirements by regulatory agencies.

Table 5.1 – Key parameters for water sampling

pH
Electrical Conductance (EC)
Temperature
Dissolved Oxygen (DO)
Total Dissolved Solids (TDS)
Total Suspended Solids (TSS)
Acidity
Alkalinity

Major Ions:	Calcium, magnesium, sodium, potassium, chloride, sulfate, nitrate, ammonia.
Metals:	Iron, aluminum, arsenic, cadmium, copper, cobalt, lead, nickel, zinc, molybdenum.
Radionuclides:	Total uranium, thorium-232, radium-226, lead-210.

5.3.2.2 *Sample collection methods*

The most common type of surface water sample collected is referred to as the discrete 'grab' sample. A grab sample represents the conditions which exist at the sampling location at the time of sampling. To take grab samples, the container is immersed into the stream to be sampled and filled. It is desirable for the container to be held well below the surface (mid-depth is preferred) although this may not be possible in shallow streams. Samples should also be taken from the middle of streams or channels if possible.

For deep bodies of water such as ponds or lakes, grab samples may be collected at the surface (approx. 0.5 metres), at specific depths, or as depth-integrated samples depending on the purpose of the sampling program. A variety of surface water sampling techniques are outlined by Environment Canada (1983). An example of a depth-specific Kemmerer sampler is shown in Fig. 5.2. This type of sampler is lowered to the depth of sampling in an open position and closed via a messenger to retain the water sample. A common type of depth-integrated sampler is the sampling iron, in which an empty two-litre bottle is lowered to the bottom and raised at a constant rate so that the bottle is just filled as it reaches the surface.

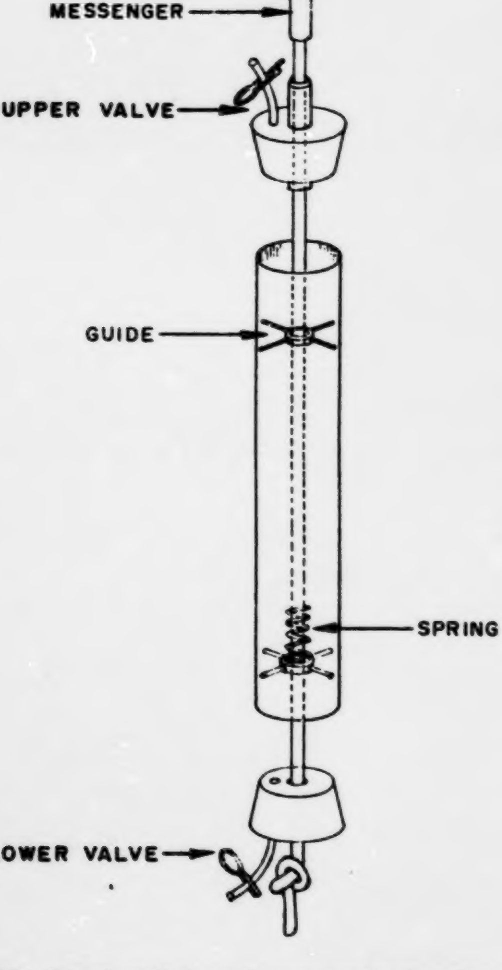


Fig. 5.2 – Example of depth-specific water sampler (Kemmerer)

Sampling personnel should be familiar with the general area where samples are taken. Prior to sample collection, sampling personnel should walk around the sampling location and note anything unusual that may influence the quality of the sample. Where possible, samples should be taken upstream of artificial constrictions (such as a culvert or bridge) or other features that might alter water quality at the sampling location. The principal objective is to collect samples that are representative of the conditions at the sampling location. Care should be taken to avoid including floating debris such as leaves in the sample. The act of taking a sample can stir up sediment from the banks or bottom and such turbidity should also be avoided.

A composite sample is obtained by mixing several discrete samples of equal or weighted volume into a single sample container. Composite samples provide estimates of average water quality conditions without the need to analyse many discrete samples. Composite samples may be time composites or flow proportional composites. Time composite samples are made up by mixing equal water volumes collected at regular time intervals. For example, a time composite of 12 monthly discrete samples of water from a specific location may be made to estimate the annual average water quality at that location. Flow proportional composite samples are made up by mixing discrete samples of water collected from several locations or at several time intervals whose volumes are proportional to the flows at the time of sampling. For example, a flow proportional composite sample may be made to estimate the average water quality of surface water inflow to a pond where there are several inflows of differing magnitudes. In this situation, the composite sample would consist of various aliquots of water from discrete samples of each inflow, with the volume of each aliquot proportional to the flow at each sample location.

Automatic sampling devices are also available which collect discrete samples at regular time intervals or combine the discrete samples to produce composite samples. Automatic samplers are relatively expensive but can perform unattended.

5.3.2.3 *Sample handling and preservation methods*

Prior to collecting samples, sampling personnel should be aware of which parameters are to be analyzed. Depending on the parameters being investigated, there are certain requirements regarding container types and sizes and the addition of chemical preservatives to the samples (see Table 5.2). The use of some preservatives precludes the analysis of certain parameters; sampling personnel should recognize these restrictions and take appropriate steps to avoid contamination and ensure that sufficient numbers of samples are collected. Time and trouble can often be saved if sampling personnel and the laboratory analyst confer in advance regarding the best techniques for sample handling and preservation.

In general, surface water samples should be collected in 1-litre containers. Polyethylene is preferred because it is rugged and does not react with most sample constituents. For samples that do not have a chemical preservative already in the collection bottle, both the bottle and the cap should be rinsed with the water to be sampled several times if possible.

Following collection, samples should be kept cool (approximately 4°C is recommended) until analyzed. The storage at cool temperatures inhibits chemical reactions such as oxidation and precipitation which can alter sample quality. If the possible growth of micro-organisms is a concern, samples should also be kept in the dark. Samples should be sent to the laboratory as quickly as possible because sample composition may change with time.

Surface water samples are not generally filtered because the 'total' concentrations (the dissolved plus suspended components) of constituents are usually of most concern in assessing the effects of loadings to surface waters. If analysis of dissolved concentration is required, water samples should be filtered prior to adding chemical preservatives. Filtration methods are described in Section 6.6.3. It should be noted that although 0.45 μm membranes are most commonly used for water samples, there is no accepted standard filter for preparation of dissolved radium analyses. Filters ranging from 0.45 to 3.0 μm have been used by different organizations and yield different results.

Table 5.2 – Water sample handling and preservation techniques

Parameter	Field analysis	Sample Container			Preservation with HNO_3 to pH<2	Maximum storage time
		Glass		Polyethylene		
pH	X					—
Electrical Conductance	X					—
Temperature	X					—
Dissolved Oxygen	X					—
TDS		X	or	X		7 days
TSS		X	or	X		7 days
Acidity		X	or	X		24 hours
Alkalinity		X	or	X		24 hours
Calcium				X	X	6 months
Magnesium				X	X	6 months
Sodium				X	X	6 months
Potassium				X	X	6 months
Chloride		X	or	X		7 days
Sulfate		X	or	X		7 days
Nitrate		X	or	X		24 hours
Ammonia				X		24 hours
Total Iron				X	X	6 months
Ferrous Iron				X	X	24 hours
Aluminum				X	X	6 months
Silica				X		7 days
Arsenic				X	X	6 months
Cadmium				X	X	6 months
Copper				X	X	6 months
Cobalt				X	X	6 months
Lead				X	X	6 months
Nickel				X	X	6 months
Zinc				X	X	6 months
Uranium				X	X	6 months
Thorium				X	X	6 months
Radium-226				X	X	6 months
Lead-210				X	X	6 months

Modified from Environment Canada (1983) and Environment Ontario (1981).
All samples should be stored at 4°C.

5.3.2.4 *Analytical methods*

Water samples collected for the analysis of pH, electrical conductance, temperature and dissolved oxygen should be analysed in the field immediately following collection due to the unstable nature of these parameters. The measurement of these parameters is readily accomplished with the use of portable test equipment. Examples of portable pH and electrical conductivity meters are shown in Fig. 5.3. Detailed descriptions of test procedures and calibration of pH, electrical conductance and dissolved oxygen equipment are found in ASTM (1983) Volume 11.01: Designations D1293-78, D1125-82 and D888-81 respectively. Special considerations for field measurements are described in Environment Canada (1983).

The analysis of surface water samples from uranium tailings impoundments can be conducted using the same methods used for the analysis of other waters and wastewaters. Standard laboratory methods for the analysis of chemical and radiological parameters are described by Environment Canada (1979), Environment Ontario (1981), the American Public Health Association (1980), the U.S. Department of the Interior (1977), and ASTM (1983) Volume 11.01.

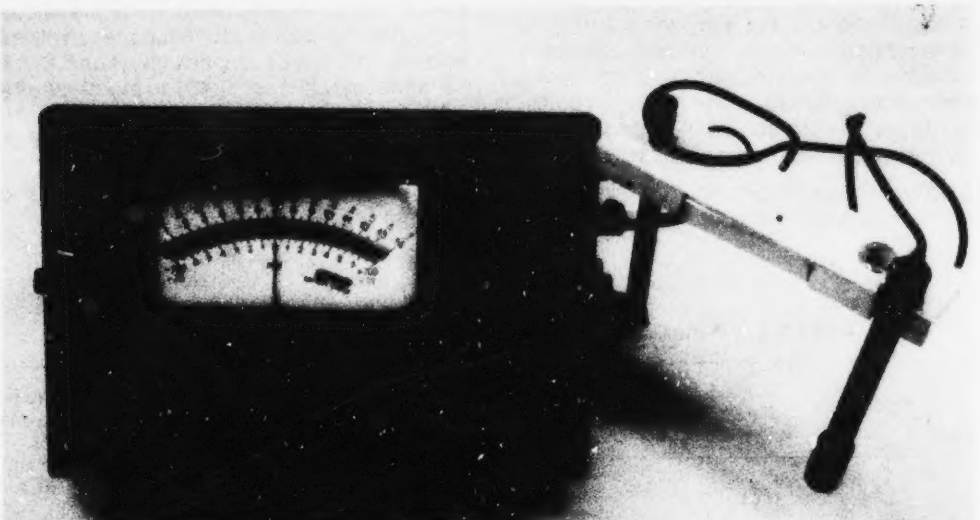


Fig. 5.3 – Typical portable pH and electrical conductance meters
A. pH meter
B. Electrical conductance meter

5.4 SEEPAGE

5.4.1 Flow Measurements

Seepage from tailings impoundments does not lend itself to easy measurement because flows are generally low, and there is a large potential for dilution by other surface waters. In the case of both distributed and localized seepage, the seepage flow must in some way be contained or collected for a flow measurement while excluding other sources of water. This may involve the construction of collector ditches or sumps in the areas of seepage. High volume seepages which result in significant surface water flows can be measured using surface water flow measurement techniques as described in Section 5.3.1. Low volume seepages from granular soils or through earth fill dams which do not produce readily measureable surface water flows can sometimes be estimated using seepage-meter techniques.

Seepage meters have been used to investigate shallow groundwater discharge to surface water streams and lakes (Lee and Cherry, 1978; Lee et al., 1980). Seepage meters consist of collection devices installed on the stream or lake bed which intercept and measure the rate of discharge of groundwater into the surface water. An example of a seepage meter is shown in Fig. 5.4. In areas of groundwater discharge or seepage, water flows upward into the seepage meter and fills the collection bag. The rate at which the collection bag fills is monitored, and the rate of groundwater discharge or seepage is calculated. The identification of groundwater discharge or seepage zones for the installation of seepage meters can be complemented by the use of mini-piezometers. Mini-piezometers consist of small diameter (<1 cm) piezometers installed manually to shallow depths (<1 m) below the stream or lake bed (see Fig. 5.5). Groundwater discharge or seepage zones are identified where water levels in the mini-piezometers are higher than the water level in the stream or pond.

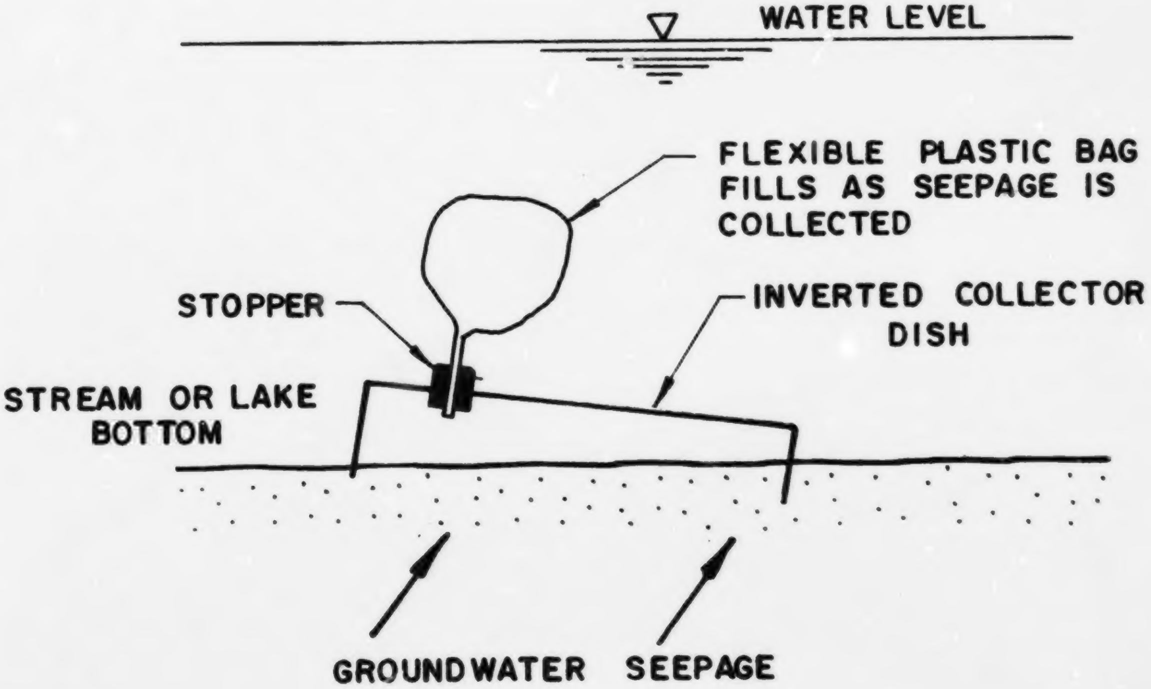


Fig. 5.4 – Seepage meters for determination of rate of groundwater discharge to surface water

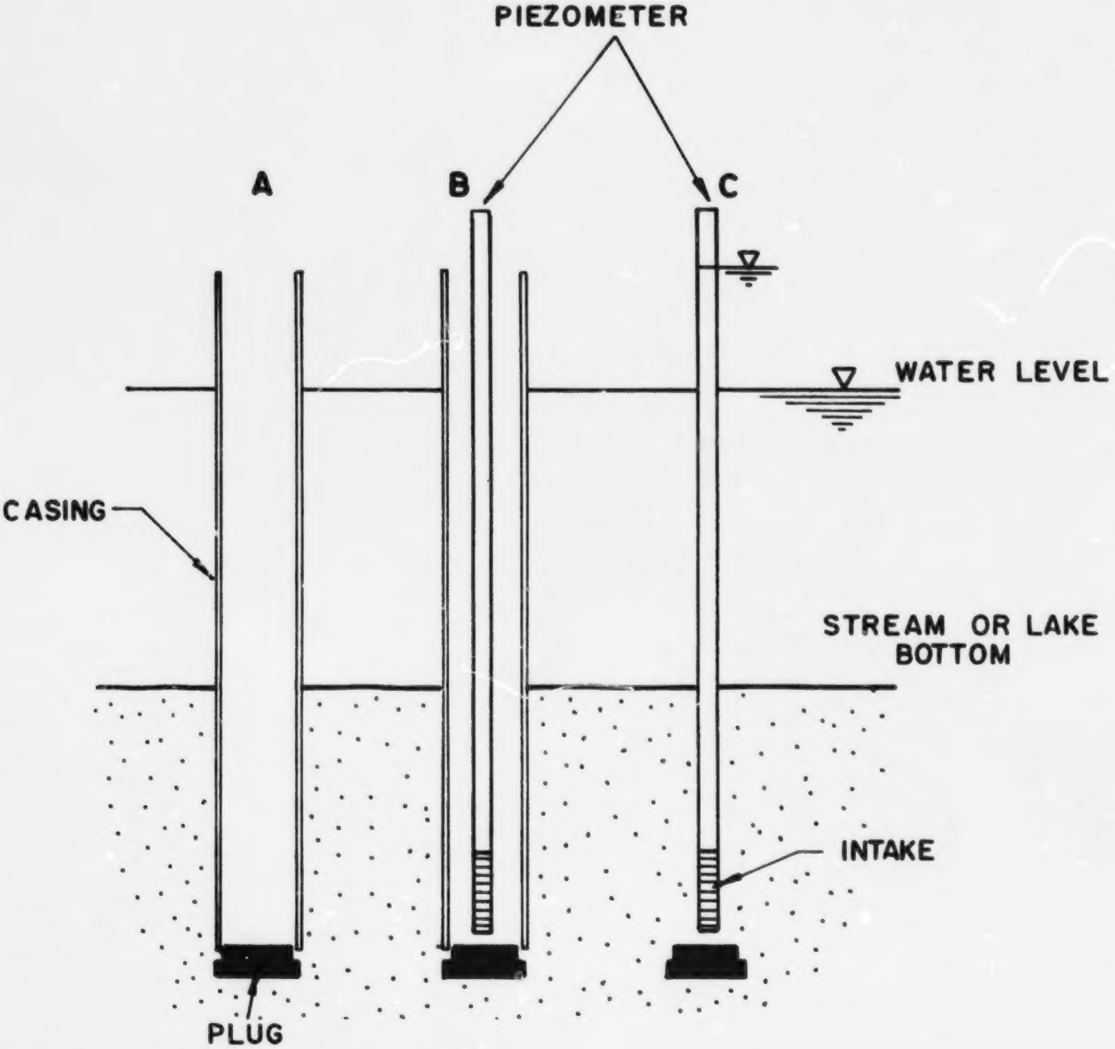


Fig. 5.5 – Installation of mini-piezometers in stream or lake bed
A. Driving of casing with removable plug
B. Insertion of piezometer into casing
C. Removal of casing

5.4.2 Chemical Sampling

5.4.2.1 Parameters

The key chemical parameters which will be important for the sampling of localized seepage are the same as those identified in Table 5.1 for surface water sampling. These parameters include indicator parameters, major ions, metals and radionuclides. As for surface water sampling this listing provides a basis for the selection of sampling parameters, but parameters may be added or deleted according to site-specific considerations.

5.4.2.2 Sample collection methods

High volume seepages which result in significant surface water flows can be sampled using the same collection methods described in Section 5.3.2.2 for surface water. Grab sampling is the most common type of collection method but automatic sampling devices can also be used.

Water samples from seepage meters and mini-piezometers can be collected from the installations as seepage fills the collection bags. The samples are then transferred to appropriate sample containers for preservation and storage. However, it should be noted that the chemical composition of water collected in seepage meters may be altered by chemical reactions with the stream/lake bottom sediments in the seepage meter. Consequently, water samples from mini-piezometers would generally be preferable for detailed assessment of seepage chemistry.

5.4.2.3 Sample handling and preservation methods

The sample handling and preservation methods described in Section 5.3.2.3 for surface water samples are also applicable to seepage samples. The recommended methods for handling and preservation of water samples are shown in Table 5.2. As noted in Section 5.3.2.3, surface water samples are not generally filtered because the 'total' (dissolved plus suspended) concentrations are usually of most interest in assessing the effects of loadings to surrounding surface water bodies. Similarly, when the effect of seepage loadings to surrounding surface water is of interest, the seepage samples are not filtered. However, when seepage sampling is intended to assist the characterization of the tailings porewater from which the seepage is derived, it is the dissolved concentrations that are of interest and consequently the seepage samples are filtered. Filtration of samples is described in Section 6.6.3.

5.4.2.4 Analytical methods

As with surface water samples, parameters such as pH, electrical conductance, temperature and dissolved oxygen should be analysed in the field immediately following collection. Detailed procedures for these measurements are referenced in Section 5.3.2.4.

The analysis of seepage samples can be conducted using the same laboratory methods used for the analysis of other waters and wastewaters. Standard methods for the laboratory analysis of chemical and radiological parameters are described by Environment Canada (1979), Environment Ontario (1981), the American Public Health Association (1980), the U.S. Department of the Interior (1977) and ASTM (1983), Volume 11.01.

5.5 QUALITY ASSURANCE FOR WATER SAMPLING

5.5.1 Recording of Field Data

The accurate and comprehensive recording of field data is a vital component of surface water sampling programs. Field data from a sampling program will include sample identification numbers, sampling locations, weather conditions, field measurements and observations, and the numbers and types of samples collected for laboratory analyses. The results of the water quality analyses cannot be properly interpreted without this type of supporting information. Field data are best recorded on prepared water sampling forms to ensure that all pertinent observations are made and the information is recorded in a standardized manner. An example of a surface water sampling form of the type recommended by Environment Canada (1983) is shown in Fig. 5.6.

5.5.2 Quality Control for Sample Collection

Water sampling equipment and sampling procedures used in water quality sampling programs will have an important influence on the reliability of the water quality results. Consequently, quality control procedures for water sample collection are important components of a comprehensive water sampling program.

Sampling equipment and sample containers should be constructed of materials which will not affect the chemical composition of the water samples. For example, as noted in Section 5.3.2.3, water samples for the detailed analysis of silica, sodium or potassium should be retained in polyethylene containers because these constituents can be leached from glass containers. Leaching of constituents could result in erroneously high results. Similarly, water samples for the detailed analyses of heavy metals should be retained in polyethylene containers because heavy metals may be adsorbed on the walls of glass containers. Adsorption of metals could result in erroneously low results.

It is also important that sampling equipment and sample containers be adequately cleaned prior to use. Sample container cleaning procedures for specific types of chemical analyses are described in Environment Canada (1983). In general, sample container cleaning procedures for parameters of interest in uranium tailings would involve:

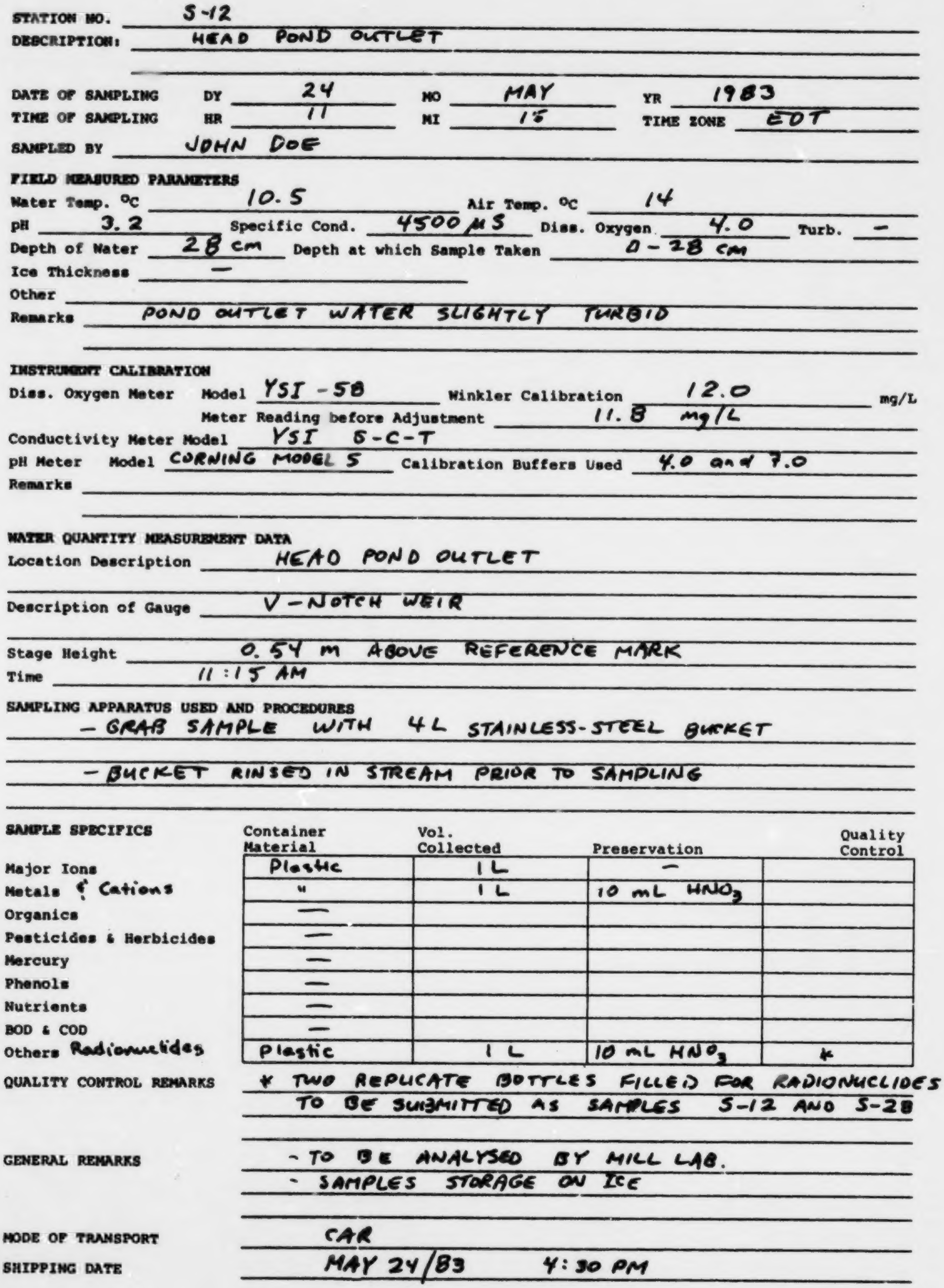
- clean tap water rinse;
- dilute acid rinse;
- distilled water rinse.

Sample containers that are excessively soiled may require additional water/detergent or chromic acid washing prior to the final acid rinse and distilled water rinse.

As noted in Section 5.3.2.3, water samples for the analyses of cations, heavy metals and radionuclides should be preserved by the addition of concentrated nitric acid to a pH <2. It is important to ensure the preservative acid is pure and will not result in contamination of the samples.

Given the potential for errors resulting from equipment and impure preservatives, quality control procedures involving the use of field blanks and field standards can be implemented to identify these sources of error in a water sampling program.

Field blanks are generally used to evaluate potential contamination of samples from contact with the sampling equipment, sample containers or sample preservatives. Field blanks are prepared in the field using laboratory-analysed distilled water. The distilled water is used to fill the water sampler and the field blank is then handled, preserved and analysed in a



STATION NO. S-12

DESCRIPTION: HEAD POND OUTLET

DATE OF SAMPLING DY 24 MO MAY YR 1983

TIME OF SAMPLING HR 11 MI 15 TIME ZONE EDT

SAMPLED BY JOHN DOE

FIELD MEASURED PARAMETERS

Water Temp. °C 10.5 Air Temp. °C 14

pH 3.2 Specific Cond. 4500 µS Diss. Oxygen 4.0 Turb. –

Depth of Water 28 cm Depth at which Sample Taken 0 – 28 cm

Ice Thickness –

Other

Remarks POND OUTLET WATER SLIGHTLY TURBID

INSTRUMENT CALIBRATION

Diss. Oxygen Meter Model YSI – 58 Winkler Calibration 12.0 mg/L

Meter Reading before Adjustment 11.8 mg/L

Conductivity Meter Model YSI 5-C-T

pH Meter Model CORNING MODEL 5 Calibration Buffers Used 4.0 and 7.0

Remarks

WATER QUANTITY MEASUREMENT DATA

Location Description HEAD POND OUTLET

Description of Gauge V-NOTCH WEIR

Stage Height 0.54 m ABOVE REFERENCE MARK

Time 11:15 AM

SAMPLING APPARATUS USED AND PROCEDURES

– GRAB SAMPLE WITH 4L STAINLESS-STEEL BUCKET

– BUCKET RINSED IN STREAM PRIOR TO SAMPLING

SAMPLE SPECIFICS	Container Material	Vol. Collected	Preservation	Quality Control
Major Ions	Plastic	1L	–	
Metals & Cations	"	1 L	10 mL HNO_3	
Organics	—			
Pesticides & Herbicides	—			
Mercury	—			
Phenols	—			
Nutrients	—			
BOD & COD	—			
Others Radionuclides	Plastic	1 L	10 mL HNO_3	*

QUALITY CONTROL REMARKS * TWO REPLICATE BOTTLES FILLED FOR RADIONUCLIDES TO BE SUBMITTED AS SAMPLES S-12 AND S-28

GENERAL REMARKS – TO BE ANALYSED BY MILL LAB.
– SAMPLES STORAGE ON ICE

MODE OF TRANSPORT CAR

SHIPPING DATE MAY 24/83 4:30 PM

Fig. 5.6 – Example of surface water sampling form (completed for a typical tailings surface water sample)

manner identical to the actual water samples collected. In this way any significant amounts of dissolved constituents which are released to the samples from the sampling equipment, sample containers or sample preservatives will be indicated in the analyses of the field blanks. If contamination of the field blanks is indicated, more detailed studies can be conducted to determine the source of the contamination. Field standards can be used to evaluate the potential loss of dissolved constituents due to adsorption on sampling equipment or sample containers. Field standards are prepared using water samples of known concentration and are treated in the same manner as field blanks. In this way, any significant adsorption or loss of dissolved constituents from the samples will be indicated by decreased concentrations in the field standards.

The reliability of water quality results will also depend on the laboratory procedures and analytical techniques used. Quality control procedures in a water analysis laboratory will include reagent/method blanks, calibration standards, laboratory controls, spiked samples, duplicate samples and replicate analyses. These procedures are described in detail by USEPA (1979) and will not be discussed here.

As an independent check of precision or reproducibility of laboratory chemical analyses, field replicate samples can be collected. Field replicate samples are two or more samples split in the field from a single water sample and are submitted to the laboratory under separate designations. The analytical results of the field replicate samples should be comparable to the expected range of precision of the analytical techniques.

5.5.3 Independent Assessment of Data Reliability

In addition to the field sampling and laboratory quality control procedures discussed in the previous sections, there are several procedures available for the independent assessment of the general reliability of water quality data. These procedures include:

- ionic balance calculations;
- EC-TDS relationships;
- EC-ionic sum relationships;
- summed TDS-measured TDS relationships.

These procedures can be used to assess the general reliability/completeness of major ion analyses of water samples by identifying possible analytical problems not detected by the laboratory quality control program, or more commonly, identifying arithmetic, transcription or reporting errors in the analytical results. These procedures are described in detail by Keith et al. (1983).

Ionic balance calculations are the most commonly used procedure for assessing water quality data reliability. The ionic balance calculation is based on the fact that water is electrically neutral and the ionic sum of the cations should equal the ionic sum of the anions. The ionic sums are calculated as the sum of the concentrations of the individual ions in equivalent parts per million (epm). Epm concentrations are calculated as the analytical concentration in parts per million (ppm) or milligrams per litre divided by the molecular weight of the ion, multiplied by the ionic charge.

The ionic balance is calculated as a percentage by:

$$\frac{(\Sigma \text{ cations} - \Sigma \text{ anions})}{(\Sigma \text{ cations} + \Sigma \text{ anions})} \times 100$$

With this expression, for a water sample in which all major ions have been analyzed and each analysis is accurate, the resultant ionic balance should be zero.

In most cases, however, the ionic balance will range from positive to negative suggesting an apparent excess of cations or anions in the analysis. Acceptable ranges for the ionic balance will vary depending on the TDS concentrations in the samples and the required accuracy of the analyses. In general, ionic balances will be poorer (either higher or lower) for very low-TDS waters and for very high-TDS waters because of poorer accuracy of analyses in these ranges. For most water samples an acceptable ionic balance will be plus or minus 5 to 10 per cent.

Ionic balance calculations larger than those considered acceptable suggest that either the water analysis is incomplete (i.e., a major constituent was not analysed) or there are errors in some of the analytical results. Poor ionic balances are a signal that the analytical results should be very carefully examined in order to identify the potential errors. Errors in laboratory sample dilution calculations and transcription of data are those most commonly identified by ionic balance calculations.

As a quality control procedure, ionic balance calculations are limited by several factors. Firstly, the ionic balance indicates only that errors may exist in the major ion analyses and does not indicate which specific analyses may be in error. Large errors in minor or trace constituents may go undetected. In addition, compensating errors in major ion analyses may go undetected.

Electrical conductance (EC)-total dissolved solids (TDS) relationships can also be used to assess the general reliability of major ion analyses. The electrical conductance of a water sample depends primarily on the concentrations of dissolved constituents and consequently will be related to the TDS concentrations. Hem (1970) reported that for most waters the TDS (in mg/L) equals 0.55 to 0.75 EC (in µmhos/cm at 25°C). When the EC-TDS relations of a water sample do not fall in this range, it may suggest that the major ion analyses are incomplete or there are errors in the analyses.

Similarly, Logan (1961) proposed several empirical formulae which can be used as a general check of major ion analyses. These formulae are shown in Table 5.3 and relate the electrical conductance (EC) to the ionic sum (B) for various conditions. When the measured EC of a water sample is significantly different than the predicted EC from these empirical EC-ionic sum relationships, it may suggest that the major ion analyses are incomplete or are in error.

A comparison of measured TDS concentrations and the sum of the individual major ion analyses (ppm or mg/L) can also be used as a quick check for major ion analyses.

5.6 PROGRAM COSTS

The costs of a surface water sampling program will depend primarily on the intensity of the program as reflected by the number of sampling and flow measurement locations, and the number of individual samples. In comparison to tailings solids and tailings porewater sampling programs, surface water sampling programs generally require little in the way of specialized or costly equipment and procedures.

An exception to this is the installation of stream flow measurement devices such as weirs and flumes. These devices require installation by experienced specialist field personnel to obtain accurate stream flow data. As an example, the installation of a small weir with a water level recorder would require approximately one day of a two person field crew plus approximately $500 to $1000 for materials and the recorder in 1984.

The collection of surface water samples is not normally labour intensive. For example, a surface water sampling program conducted by a single field person will typically involve collection of 10 to 25 samples per day depending on the accessibility of the sampling locations and the field measurements which are required.

Table 5.3 – Empirical electrical conductance (EC)-ionic sum (B) relationships

From Logan (1961)

	Conditions	Formula
1.	$B < 1.0$	$EC = 100\,B$
2.	$1.0 < B < 3.0$	$EC = 12.27 + 83.38B + 0.835\,B^2$
3.	$3.0 < B < 10.0$	$EC = 13\,[95.5 - 5.54\,(\log B)]$
4.	$B > 10.0$ Bicarbonate Dominant Anion	$EC = 90\,B$
5.	$B > 10.0$ Chloride Dominant Anion	$EC = 123\,B^{0.939}$
6.	$B > 10.0$ Sulfate Dominant Anion	$EC = 101\,B^{0.949}$
Where	$B = \frac{\Sigma \text{ cations (epm)} - \Sigma \text{ anions (epm)}}{2}$	

5.7 REFERENCES

American Public Health Association (1980). Standard Methods for the Examination of Water and Wastewater.

American Society for Standards and Testing (ASTM) (1983). 1982 Annual Book of ASTM Standards, Part 11.01: Water.

D888-81	Test methods for dissolved oxygen in water.
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D1293-78	Test methods for pH of water.
D1941-67	Method for open channel flow measurement of water and wastewater by the Parshall flume.
D2034-68	Method for open channel flow measurement of water by weirs.
D3370-82	Practices for sampling water.
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6. TAILINGS POREWATER

6.1 OBJECTIVES

The overall objective of tailings porewater sampling is to characterize and monitor the movement and chemical composition of the porewater which occurs in the tailings. The movement and chemical composition of the porewater in the tailings will have a great influence on the quantity and quality of surface water runoff, localized seepage and exfiltration from the tailings impoundment.

The movement of porewater through the tailings is controlled by the hydrogeologic conditions within and around the tailings impoundment. The chemical composition of the tailings porewater is controlled by the chemical composition of the mill effluent and chemical reactions within the tailings.

The characterization of the movement and chemical composition of tailings porewater in the saturated zone of the tailings (below the water table) normally involves the installation of piezometers or monitoring wells. The piezometers allow the measurement of hydraulic head and consequently porewater flow directions, the measurement of hydraulic conductivity, and the collection of porewater samples for chemical analysis. There is also a wide variety of specialized hydraulic, pneumatic, and vibrating-wire piezometers available for the measurement of hydraulic head. These do not allow hydraulic conductivity testing or water sampling. These devices are generally of limited application in tailings sampling programs. The movement and chemical composition of porewater in the unsaturated zone (above the water table) can also be important in some situations. For example, in poorly buffered pyritic tailings, pyrite oxidation occurs predominantly in the unsaturated zone close to the surface of the tailings and can control the chemical composition of the porewater in the saturated zone. Characterization of the movement and quality of the porewater in the unsaturated zone of the tailings normally involves the installation of tensiometers and lysimeters or the use of coring-squeezing methods.

6.2 SELECTION OF SAMPLING LOCATIONS

Locations for the sampling of tailings porewater should be selected in order that porewater levels and porewater samples are representative of the conditions within the tailings impoundment. Sampling locations must be distributed both areally and vertically throughout the tailings impoundment to allow adequate definition of the range in porewater chemistry and porewater flow directions. The large size of most tailings impoundments and the general high cost of materials, installation and sampling precludes the selection of sampling locations according to a systematic sampling grid. Therefore, sampling locations are selected on the basis of the anticipated hydrogeologic conditions within the tailings impoundment. Factors such as the physical and chemical character of the tailings, and the depth to the water table should be considered in the selection of sampling locations. The example illustrated in Section 4.2 for the selection of tailings solids sampling locations is directly applicable to the selection of porewater sampling locations. Generally, tailings porewater sampling is conducted in conjunction with a tailings solids sampling program so that the results of the porewater sampling can be related to the physical and chemical character of the tailings.

6.3 PIEZOMETER CONSTRUCTION AND INSTALLATION

Piezometers are installed in the saturated zone of the tailings to allow the measurement of porewater levels, the determination of the in situ hydraulic conductivity of the tailings and the collection of porewater samples for chemical analysis.

In this manual, piezometers or sampling wells refer to installations having relatively short intakes (<150 cm) in order to monitor hydraulic head and collect samples from specific depths. These installations differ from wells with long intakes (>150 cm) which are used for pumping tests or the collection of depth-integrated porewater samples. Because tailings are generally heterogeneous and may exhibit large variations in hydraulic head, hydraulic conductivity and porewater chemical composition with depth, profiles of these parameters with depth are generally required. Depth profiles can be obtained from a cluster or nest of individual piezometers installed at increasing depths in the tailings, from multiple piezometers stacked in a single borehole, or from multiple-depth piezometers. Multiple small diameter piezometers or water samplers can be stacked at various depths in a single borehole. These stacked installations depend on reliable placement of sand filter packs and low permeability backfill seals for each piezometer (see Figures 6.1 and 6.5), but caving of the borehole and piping of tailings into the drill casing may prevent such installations. Although multiple-depth piezometers have been used extensively for hydrogeologic investigations in sand aquifers, they may be of limited use in most tailings. The installation of multiple-depth piezometers relies on adequate caving of the geologic materials around the piezometer to prevent vertical leakage along the piezometers. In layered silty tailings caving may not be sufficient. Consequently, nests of piezometers are normally used in tailings.

Piezometers and wells for use in tailings impoundments should be constructed of PVC or other plastic due to the normally corrosive nature of tailings and tailings porewater. Mild steel or galvanized steel piezometers may corrode and contaminate porewater samples with heavy metals. Stainless steel would be suitable but is 5 to 10 times the cost of PVC.

Piezometers can be driven or pushed into the tailings by hand or by machine, or can be installed in hand or machine drilled boreholes. The installation of piezometers and wells by hand is an advantage on tailings impoundments where the site is inaccessible to equipment such as drill rigs. Hand installed piezometers are, however, often restricted to relatively shallow depths of less than 5 to 8 m, particularly in coarse sandy tailings. In addition, the installation of piezometers by hand does not normally allow the collection of tailings solids samples, as would be obtained by drill rig methods. The various types of piezometers which are applicable for use in uranium tailings impoundments in various situations are listed in Table 6.1 together with their respective applications and limitations. The construction of these types of piezometers is illustrated in Fig. 6.1 to 6.5. Further details regarding the construction and use of these piezometers are found in the references noted in Table 6.1. Of these piezometer types, only the conventional monitoring wells and some gas-drive samplers are available commercially. The remainder must be specially constructed.

From Table 6.1 it is evident that no single type of piezometer installation will be ideally suited to all situations. The selection of the type of piezometer for use in a sampling program will depend on factors such as the accessibility of the tailings impoundment for drilling equipment, the chemical stability of the porewater and the anticipated porewater sample collection methods. The cost of the piezometer installations will be another factor to be considered. In general, small diameter (<2 cm) piezometers are much less expensive than large diameter piezometers. This difference in cost may be significant when multiplied by a large number of installations for an extensive sampling program. The rationale for the selection of the type of piezometer required is discussed together with the selection of sample collection methods in Section 6.6.2.

Table 6.1 – Types of piezometers for measurement of hydraulic head and porewater sampling

Type	Application	Limitations	Reference
1) Conventional Monitoring Well	— Installation of one well per borehole. — Large diameter wells allow the greatest flexibility for the use of different sampling methods.	— Collection of data from several depths requires additional installations and can become costly.	(1)
2) Drive-point	— Can be installed manually to eliminate need for drill rig when accessibility is a problem.	— Depth of installation may be limited by the nature of the tailings. — Tailings samples are not recovered during installation.	(2)
3) Gas-drive Samplers	— Can be installed individually or at multiple depths in a single borehole. — Will readily allow collection of samples where water levels are deep (>8 m).	— Costly — Samples can only be collected by air-lift and may be relatively disturbed.	(3)
Multiple-Depth Installations			
4) Bundle-type Piezometers	— Installation of multiple small diameter piezometers in a single borehole. — Inexpensive method for obtaining data from several depths.	— Small diameter piezometers limit the use of many sample collection methods. — Can only be installed properly in cohesionless geologic materials.	

References
1) USEPA (1977)
2) Desaulniers (1983)
3) Morrison and Brewer (1981)
4) Gillham et al. (1983)

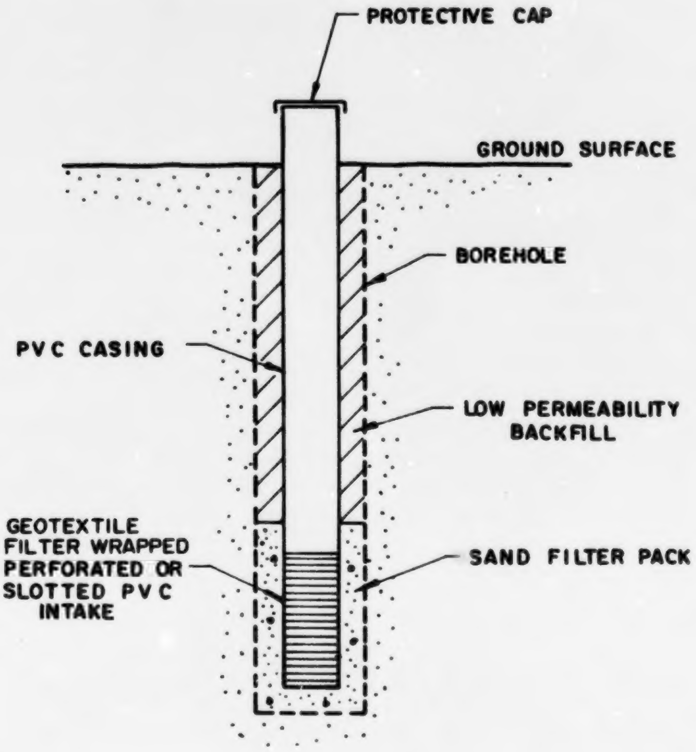

PROTECTIVE CAP
GROUND SURFACE
BOREHOLE
PVC CASING
LOW PERMEABILITY BACKFILL
GEOTEXTILE FILTER WRAPPED PERFORATED OR SLOTTED PVC INTAKE
SAND FILTER PACK

Fig. 6.1 – Conventional monitoring well

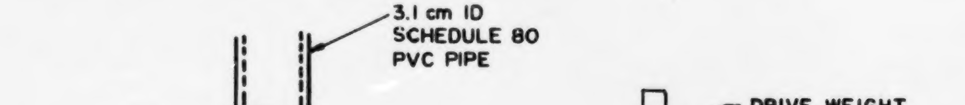
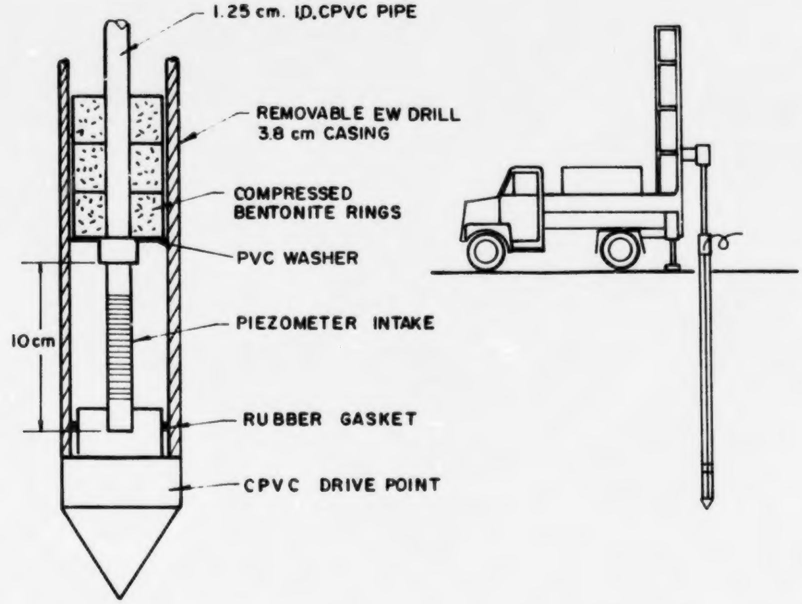

3.1 cm ID SCHEDULE 80 PVC PIPE
COUPLING
PERFORATED BARREL
15 cm.
POROUS PLASTIC CARTRIDGE
P.V.C. DRIVE POINT
PIEZOMETER TIP
DRIVE WEIGHT
DRIVE HEAD
GROUND SURFACE
COUPLING
RISER PIPE
PIEZOMETER TIP
MANUAL INSTALLATION

Fig. 6.2 Large diameter drive-point piezometer and manual installation procedure


1.25 cm. I.D.CPVC PIPE
REMOVABLE EW DRILL
3.8 cm CASING
COMPRESSED
BENTONITE RINGS
PVC WASHER
10cm
PIEZOMETER INTAKE
RUBBER GASKET
CPVC DRIVE POINT

PIEZOMETER TIP

INSTALLATION WITH DRILL RIG

Fig. 6.3 – Small diameter drive-point piezometer and drill rig installation procedure

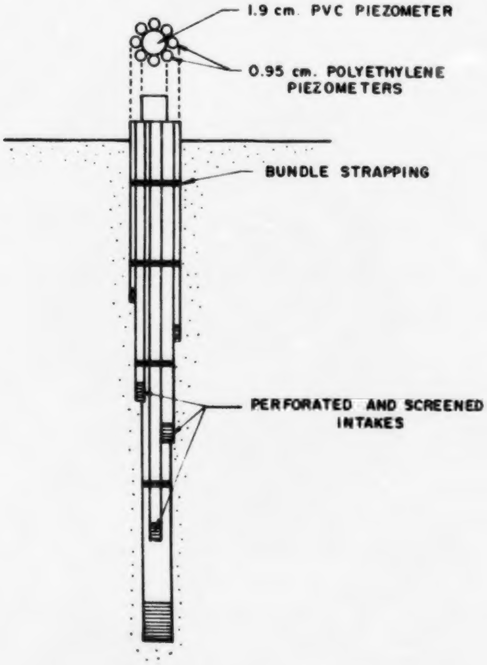

1.9 cm. PVC PIEZOMETER
0.95 cm. POLYETHYLENE
PIEZOMETERS
BUNDLE STRAPPING
PERFORATED AND SCREENED
INTAKES

Fig. 6.4 – Bundle-type piezometer

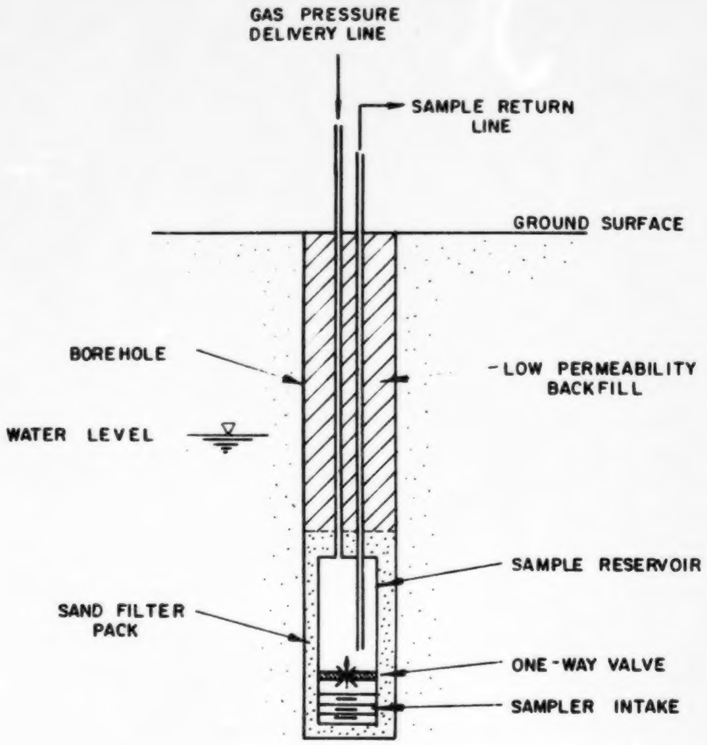


Fig. 6.5 – Gas-drive water sampler

6.4 HYDRAULIC HEAD MEASUREMENTS

Hydraulic head measurements in tailings impoundments are used to determine porewater flow directions, and are used together with hydraulic conductivity measurements to determine porewater flowrates. Hydraulic head in the saturated zone of the tailings is determined from the elevation of water levels measured in piezometers. Water levels in piezometers are normally measured periodically using electric water sounding tapes. Such devices operate by the closing of an electric circuit upon contact with the water in the piezometer and are normally accurate to within less than one centimetre. Electric water sounding tapes can be obtained commercially or can be specially constructed. Long-term continuous hydraulic head recording can be accomplished in piezometers or wells using commercially available float recorders, pressure transducers or electric sensors which are installed and left in the piezometer.

Hydraulic head in the unsaturated zone of the tailings is determined from the degree of soil suction measured in tensiometers. Tensiometers are used routinely in agriculture and soil science applications and are described in detail by Black (1965). An example of a mercury column tensiometer is shown in Fig. 6.6. Although the measurement of hydraulic head in the unsaturated zone of a tailings impoundment is not normally a consideration, the evaluation of the discharge of tailings porewater to surface water streams on the tailings and the influence of infiltration into the tailings would require such measurements.

6.5 HYDRAULIC CONDUCTIVITY TESTING

As noted in the preceding section, hydraulic conductivity measurements in the tailings are used together with hydraulic head measurements to determine porewater flow rates in the tailings. The two basic types of testing which can be used to determine the hydraulic conductivity of saturated tailings are:

- in situ tests in piezometers and wells;
- laboratory tests on tailings samples.

In situ hydraulic conductivity testing includes single-well response tests and pumping tests. The application and limitations of these tests are shown in Table 6.2. The basic principles of these in situ tests are illustrated in Figures 6.7 and 6.8. Details of these testing procedures are found in the references noted in Table 6.2.

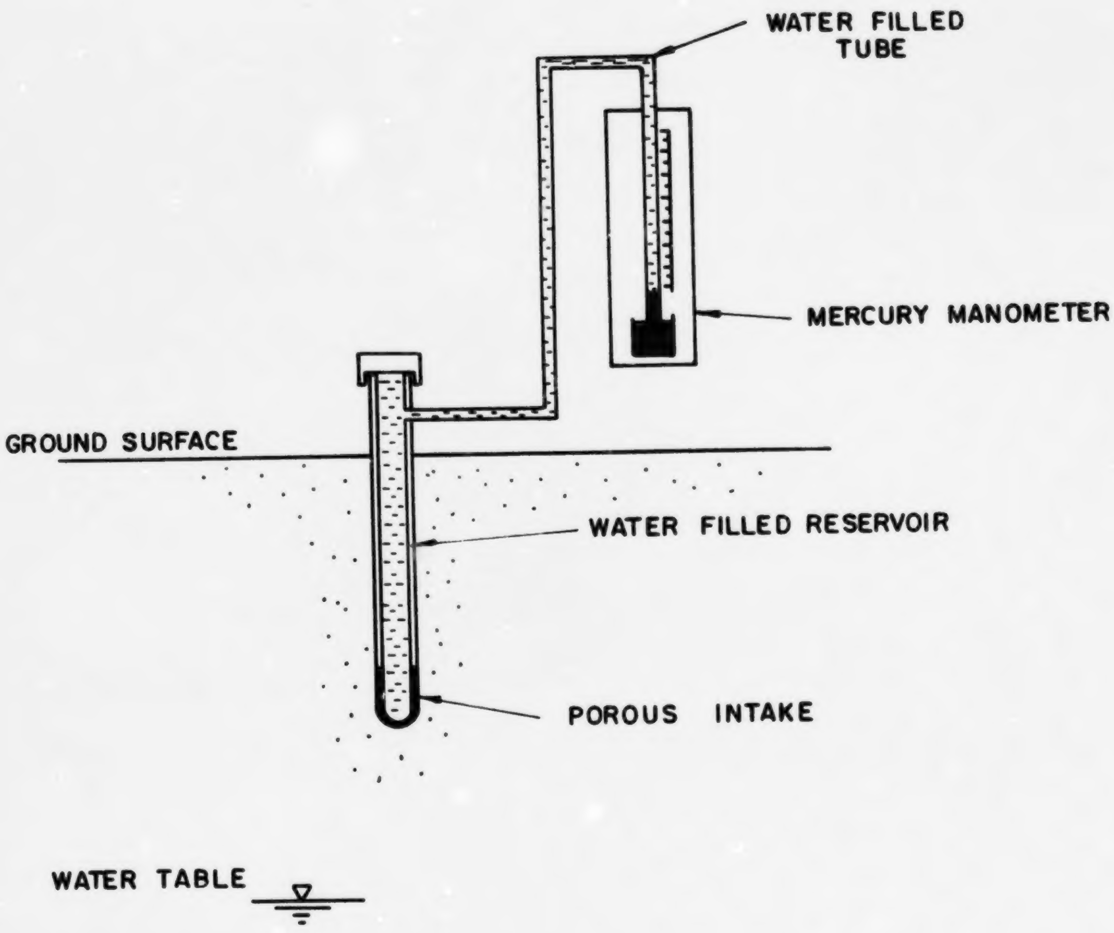


Fig. 6.6 – Tensiometer for measurement of hydraulic head in the unsaturated zone

Single-well response testing was originally formulated by Hvorslev (1951) and the calculation of horizontal hydraulic conductivity is based on the rate of the water level recovery in a piezometer following an induced change in water level. The water level change can be induced by the addition of water to the piezometer as in a falling-head test, or the removal of water as in a rising-head test. Single-well response tests, and specifically rising-head tests, are readily incorporated into a tailings porewater sampling program. The tests utilize existing piezometer installations which are also used to measure hydraulic head and collect porewater samples. Rising-head tests can be conducted during the course of piezometer purging and recovery prior to porewater sampling operations. The hydraulic conductivity of uranium tailings normally ranges from 10^{-4} cm/s to 10^{-6} cm/s so the water level recovery in piezometers occurs over the period of minutes to hours and is readily measured.

Single-well response tests in a network of piezometers allow a large number of hydraulic conductivity measurements distributed areally and vertically throughout a tailings impoundment. Due to the generally heterogeneous nature of tailings within an impoundment, this type of spatial characterization is highly desirable. The principal limitation of single-well response tests is that the vertical hydraulic conductivity cannot be determined, and this parameter is important in evaluating vertical porewater flowrates through the tailings.

The calculation of hydraulic conductivity using *pumping tests* is based on the rate of drawdown of water levels in a network of observation wells due to removal of water from a test well. A pumping test is a basic technique in hydrogeologic studies and is used to determine bulk or average hydraulic conditions. For typical pumping test analyses, plots of drawdown versus time are compared to published type-curves (see Fig. 6.8). Values for analytical parameters 1/u and W(u) are determined for specific values of time and drawdown and are used in various formulae to determine the hydraulic conductivity. The design and analysis of pumping tests are described in detail by Kruseman and De Ridder (1970). Pumping tests are costly because they normally require a special pumping well, a network of observation wells, and are generally conducted over a period of several days. The high cost of pumping tests would generally preclude a program of many tests at different locations in a tailings impoundment but without many such tests, the heterogeneities in the tailings impoundment can not be adequately assessed. Pumping tests can, however, be used to determine vertical hydraulic conductivity if a specialized network of observation wells is used. Details of this method are described by Walton (1979).

Laboratory hydraulic conductivity testing includes direct methods such as permeameter testing and triaxial permeability testing, and indirect methods such as grain-size correlation. The application and limitations of these methods are shown in Table 6.2.

Table 6.2 – Types of hydraulic conductivity testing techniques

Type	Application	Limitations	Reference
In Situ			
1) Single-well response test	— Allows rapid determination of hydraulic conductivity in porewater sampling piezometers. — Allows numerous tests to assess spatial variability.	— Zone of influence for each test is small. — Determines only horizontal hydraulic conductivity.	(1) (2)
2) Pumping test	— Allows determination of bulk hydraulic conductivity.	— Generally requires a special pumping well with observation piezometers. — Tests are generally long-term and costly. — Can only determine vertical conductivity with special monitoring configuration.	(3)
Laboratory			
3) Grain-size correlation	— Relates grain size of tailings sample to hydraulic conductivity of the sample.	— Based on empirical relationships and are only approximations. — Generally only application to sandy materials.	(4)
4) Permeameter	— Based on flow rates through undisturbed or remoulded samples to determine hydraulic conductivity. — Primarily for relatively permeable sandy tailings. — Tests on disturbed core samples provide vertical hydraulic conductivity.	— Uncertainty whether laboratory determined values represent in situ conditions.	(5)
5) Triaxial test	— Based on same principles as the permeameter tests but primarily for low permeability silty tailings.	— Same as permeameter.	(6)

References
1) Hvorslev (1951)
2) Cedergren (1967)
3) Kruseman and De Ridder (1970)
4) Freeze and Cherry (1979)
5) Black (1965)
6) Tavenas et al. (1983)

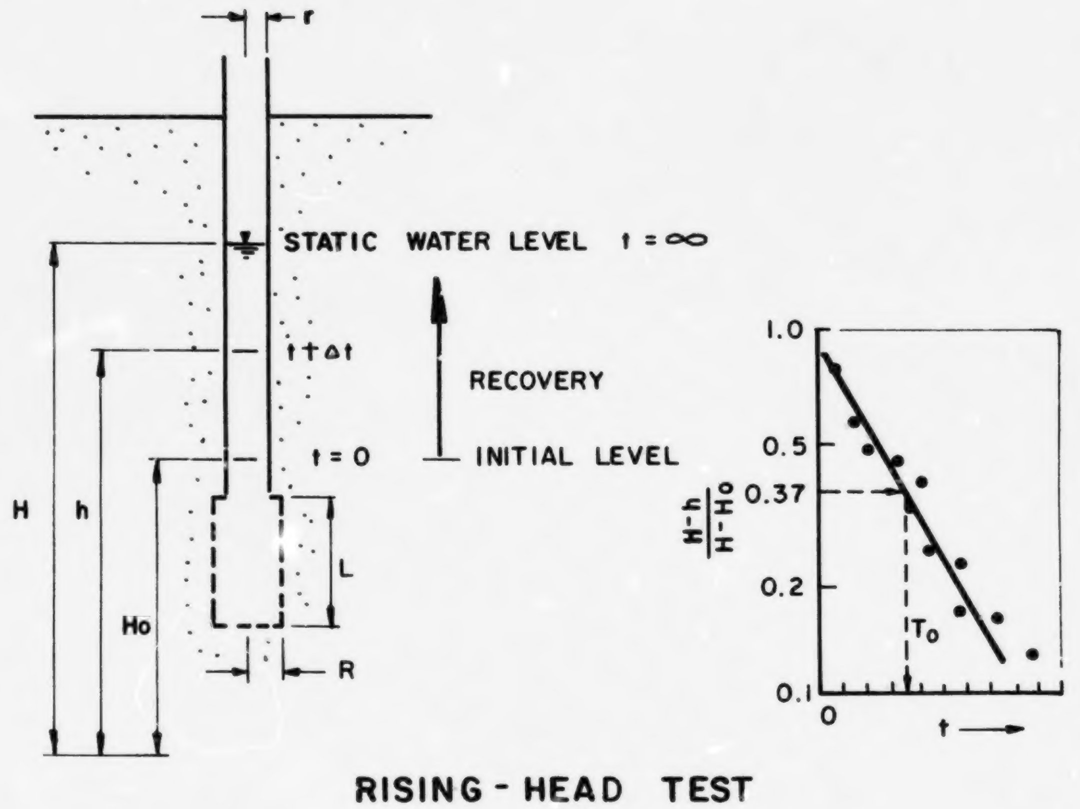


Fig. 6.7 – Single-well response test configuration and analysis to determine horizontal hydraulic conductivity (Kh)
where r is the well casing radius (cm)
R is the well intake or sand pack radius (cm)
L is the well intake length (cm)
T_o is the basic time lag from the graph (s)
m is $(K_h/K_v)^{1/2}$ usually assumed to equal 1

Laboratory hydraulic conductivity testing of undisturbed tailings samples is likely the most effective method for determining vertical hydraulic conductivity.

Grain-size correlation is based on the empirical correlation between the hydraulic conductivity of a soil sample and the grain size of the sample. Freeze and Cherry (1979) describe various grain-size correlations of which the most commonly used is:

$$\text{Hydraulic conductivity (cm/s)} = (D_{10})^2$$

where D_{10} is the grain size in mm of the 10th percentile of the grain-size distribution curve. Such empirical relations were originally determined to provide rough but useful estimates for most fine to coarse sandy materials. Empirical grain-size correlations are not likely applicable to materials with significant silt or clay contents.

Both permeameter and triaxial hydraulic conductivity testing methods are based on measurement of fluid flowrates through tailings samples of known size under known hydraulic gradients. Procedures for the laboratory determination of hydraulic conductivity using a permeameter are described by Black (1965) and ASTM (1983) Volume 04.08: D2434-68. An example of a falling-head permeameter apparatus is shown in Fig. 6.9. The configuration of triaxial testing apparatus is basically the same as the permeameter with the exception that the sample is enclosed in a rubber sleeve and is confined under a known pressure to simulate in situ confining pressures, and the test can be conducted under constant-head conditions. Constant-head tests are required for testing low hydraulic conductivity samples. Procedures for triaxial hydraulic conductivity testing are described by Tavenas et al. (1983).

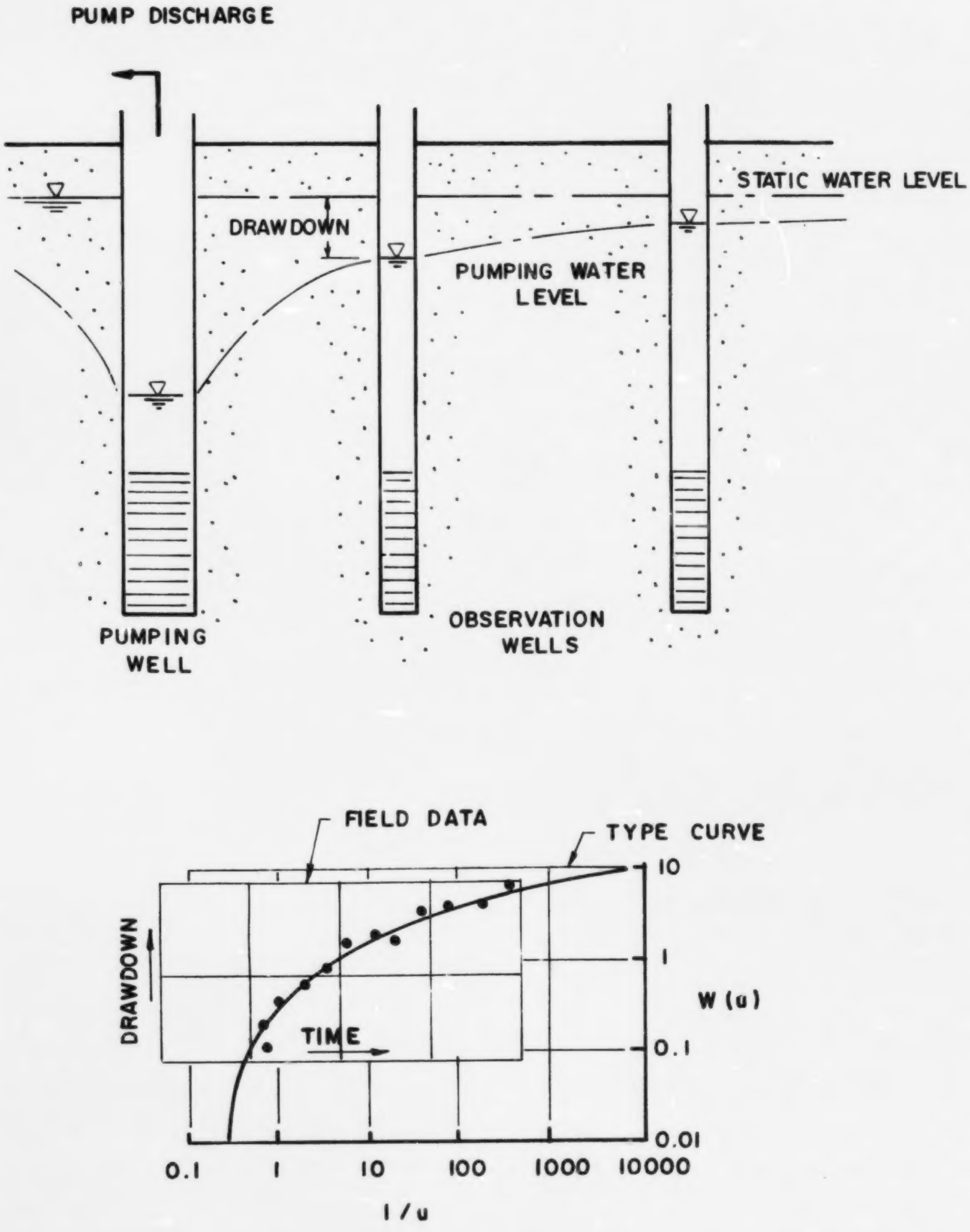

PUMP DISCHARGE
STATIC WATER LEVEL
DRAWDOWN
PUMPING WATER LEVEL
PUMPING WELL
OBSERVATION WELLS
FIELD DATA
TYPE CURVE
DRAWDOWN
TIME
W (u)
10
1
0.1
0.01
0.1
1
10
100
1000
10000
1 / u

Fig. 6.8 – Pumping test configuration and analysis to determine hydraulic conductivity

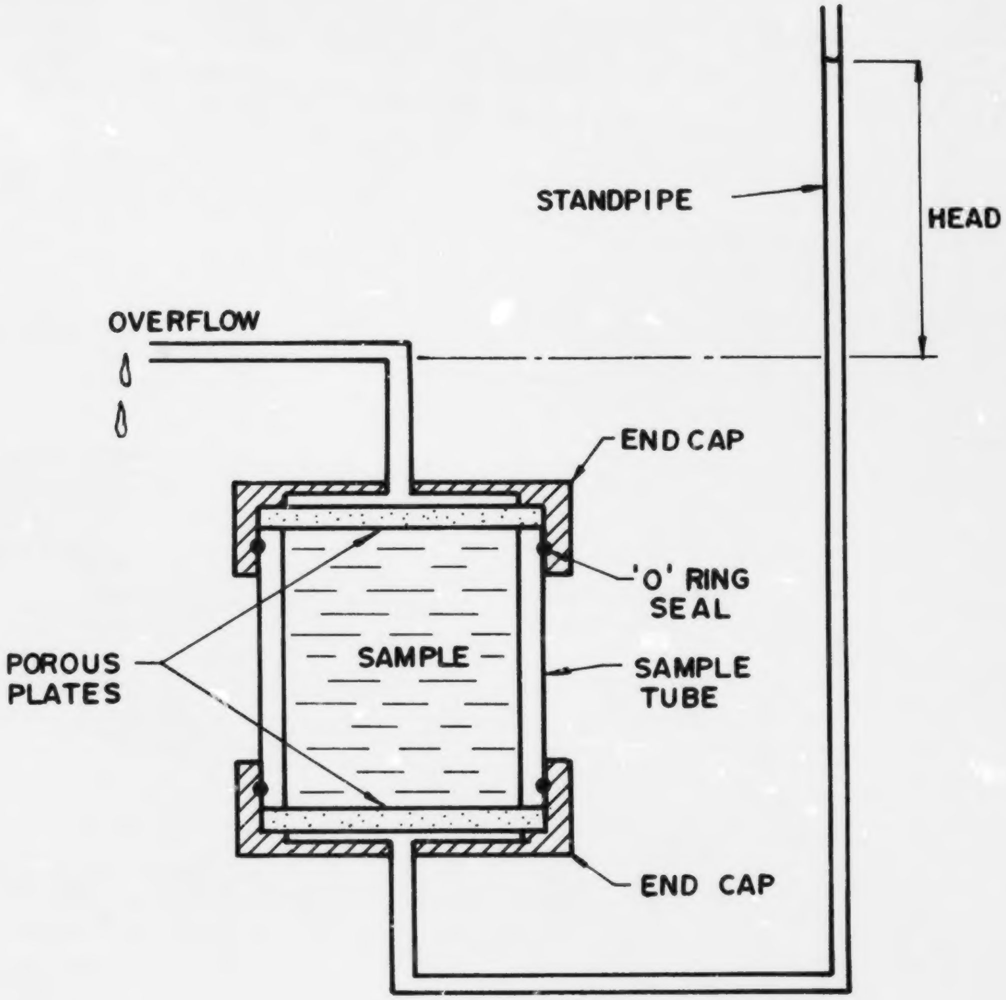


Fig. 6.9 – Permeameter apparatus for laboratory determination of hydraulic conductivity

6.6 POREWATER SAMPLING

6.6.1 Parameters

The key chemical and radiological parameters for the analysis of tailings porewater are the same as those shown in Table 5.1 for surface water sampling. As with the surface water sampling, the precise selection of parameters will be highly site-specific depending on factors such as the composition of the tailings, the chemical composition of the mill effluent and particular requirements from regulatory agencies.

6.6.2 Sample Collection Methods

Saturated Zone

A wide variety of sample collection methods can be used to recover porewater samples from piezometers and wells. These sample collection methods are listed in Table 6.3 along with their respective applications and limitations. Examples of the various sample collection devices are illustrated in Figures 6.10 to 6.13. Details on the various sample collection methods are found in the references noted in Table 6.3 and Figures 6.10 to 6.13.

Table 6.3 – Porewater sample collection methods

Type	Application	Limitations	Reference
Saturated Zone			
1) Bailers	— Simple, inexpensive method for collection of samples.	— Samples are highly disturbed and must be extensively handled during filtration. — Can be time consuming in small diameter wells.	(1)
2) Depth-specific bailer	— Simple, inexpensive method less disruptive than bailer.	— Requires relatively large diameter wells.	(1)
3) Syringe sampler	— Allows collection of samples without exposure to the atmosphere and allows filtration down-the-hole. — Can collect samples from any depth.	— Only small volumes of porewater are collected in each syringe. — Requires piezometers greater than 3 cm diameter.	(2)
4) Suction-lift pumping	— For collection of relatively large volumes of water from shallow depth. — Permits use of in-line filters to reduce sample handling.	— Sampling limited to water depths less than 8 m.	
5) Submersible pump	— For collection of large volume samples from depths greater than 8 m.	— Requires relatively large diameter wells. — Costly.	
6) Air-lift pumping	— For collection of water samples from conventional wells or special air-lift samplers. — No limitation on depth of water.	— Samples can be highly disturbed.	(3)
Unsaturated Zone			
7) Suction lysimeters	— For collection of porewater samples from unsaturated zone above the water table. — Allows repeated monitoring.	— Reliable only in relatively coarse sandy materials.	(4)
8) Core squeezing	— For collection of porewater from tailings solids samples by squeezing or displacement.	— Destructive sampling, monitoring at precisely the same location is not possible.	(5)

References

1) Gillham et al. (1983)
2) Gillham (1982)
3) USEPA (1977)
4) Everett (1981)
5) Smyth (1981)

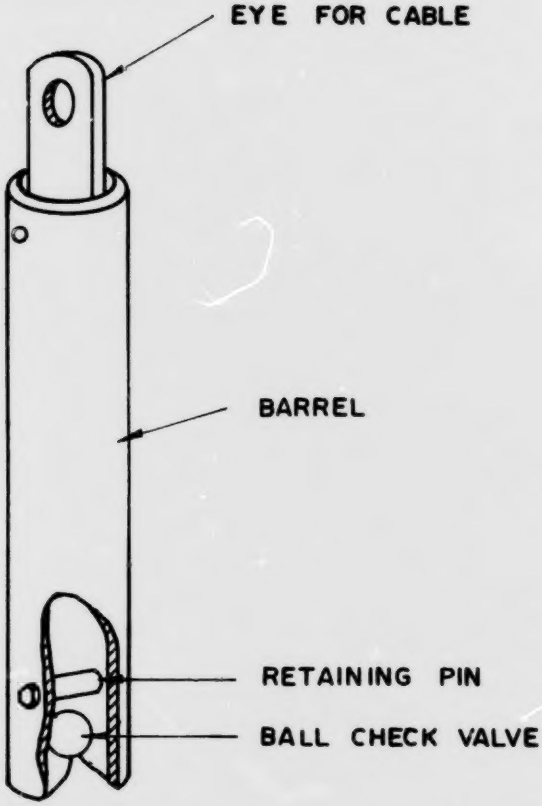

EYE FOR CABLE
BARREL
RETAINING PIN
BALL CHECK VALVE

Fig. 6.10 – Bailer for water sampling from wells and piezometers

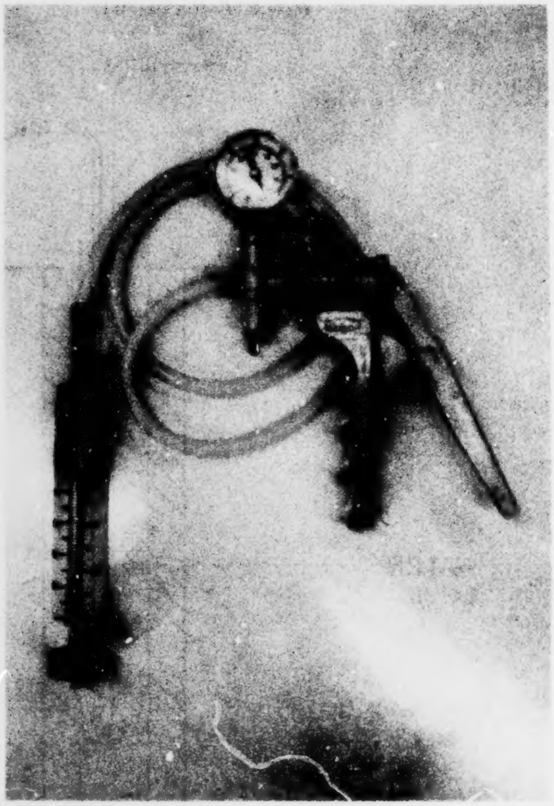


Fig. 6.11 – Syringe sampler for water sampling from wells and piezometers

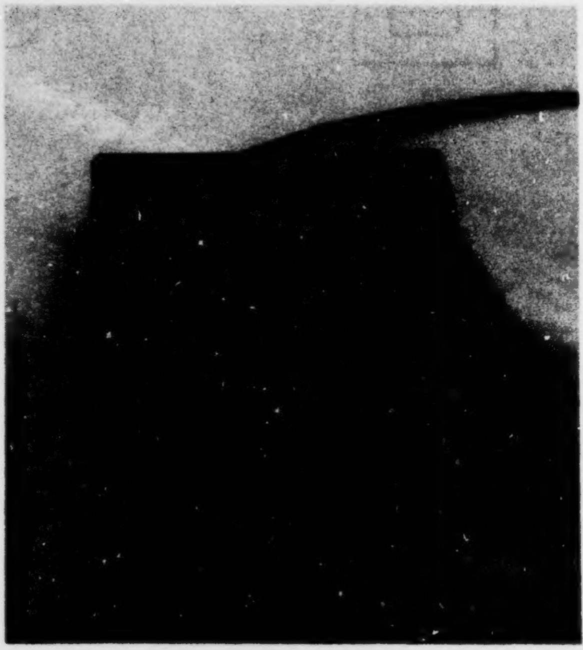


Fig. 6.12 – Example of peristaltic sampling pump

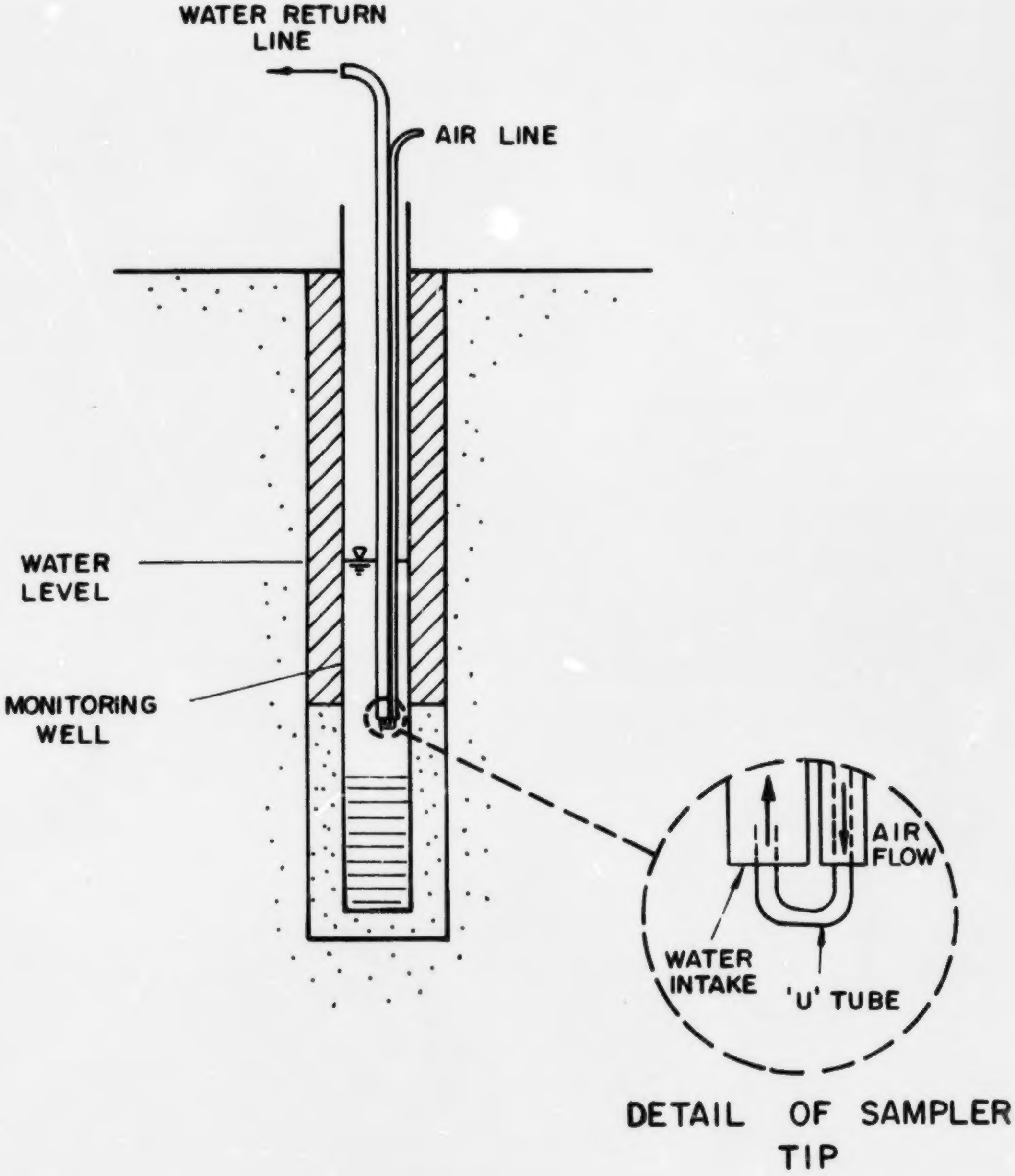


Fig. 6.13 – Air-lift device for water sampling from wells and piezometers

Prior to the collection of porewater samples from piezometers, the water standing in the piezometers must first be purged to ensure that the water which is collected represents 'fresh' porewater. Water which has remained in piezometers for extended periods of time (days or more) can undergo considerable changes in chemical composition due to degassing, oxidation and precipitation reactions within the piezometer. In piezometers which yield a continuous supply of water, it is recommended that a volume equivalent to several times the volume of the piezometer be removed prior to sample collection (Gillham et al., 1983). Piezometers which do not yield a continuous supply of water can simply be purged until they are dry and allowed to refill with 'fresh' porewater.

Devices for the collection of samples should be constructed of resistant materials such as plastic, PVC, teflon and stainless steel due to the corrosive nature of tailings porewater. The use of other less resistant materials would result in undue damage to the sampling equipment and potential contamination of the samples.

The selection of the most applicable sampling method will depend on factors such as the chemical stability of the porewater, the depth of the water table and the type of piezometer. The rationale for the selection of appropriate sample collection methods is illustrated in Fig. 6.14 together with the selection of the type of piezometer required.

An important consideration in the selection of piezometer type and sample collection method is accessibility on the tailings impoundment. If the site accessibility is poor then the piezometer installations may be restricted to those which can be installed manually.

The chemical stability of the tailings porewater will affect the size or diameter of the required piezometer. Tailings porewater which contains high concentrations of ferrous iron (>100 mg/L) is highly unstable, and the oxidation of this ferrous iron cannot be reliably prevented during conventional sample collection, filtration and preservation at the ground surface. Consequently, tailings porewater which is highly unstable should be sampled using the syringe sampler method in which the sample is recovered in a syringe lowered down the piezometer. The syringe sampling method normally requires a relatively large diameter (>3 cm) piezometer. However, special narrow diameter syringe-type samplers could be developed for use in smaller piezometers if required.

A typical syringe sampler consists of a modified 50 mL plastic syringe as shown in Fig. 6.11. The syringe sampler is fitted with a plastic 25 mm filter holder and 0.45 μm filter membrane and is lowered down the piezometer to the level of the piezometer intake. A vacuum pump is used to actuate the syringe plunger and draw water through the filter and into the syringe. The syringe sampler is then removed from the piezometer and immediately capped to prevent exposure to the atmosphere. Preservatives, if required, are added using a 1 mL plastic syringe. Syringe sampling methods have been used successfully for sampling high-iron porewater at the Denison, Stanrock and Nordic tailings impoundments at Elliot Lake (Feenstra et al., 1981; Cherry et al., 1980).

The depth to water in the tailings impoundment will affect the possible sample collection methods which can be used, which will in turn determine the type of piezometer. The depth to water is only a factor for the sampling of chemically stable porewater. The syringe sampling method for unstable porewater can operate at any depth.

In situations where the water level in the piezometers is within 6 m of the ground surface, suction-lift pumping is probably the most efficient method of sample collection, although several other methods can be used.

There is a wide variety of reliable, inexpensive, portable (suction-lift) peristaltic pumps available commercially which are well suited for porewater sampling. An example of a portable peristaltic pump is shown in Fig. 6.12. These pumps are capable of pumping rates up to approximately 1 L/min and can accommodate in-line filtration equipment. Although air-lift pumps and bailers can be used for sampling from shallow depths, sample filtration and handling are more difficult. Similarly, submersible pumps can also be used for sampling from shallow depths but are relatively costly and more time consuming to set up and operate.

In situations where the water level in the piezometers is greater than 6 m below ground surface, bailers, air-lift pumps, air-lift samplers or submersible pumps must be used because the water levels are below suction-lift range. However, in most situations at uranium tailings impoundments in Canada, it is unlikely that water levels in the tailings will be as deep as 6 m.

Unsaturated Zone

Tailings porewater samples can be collected from the unsaturated zone of the tailings using suction lysimeters or coring-squeezing methods. The applications and limitations of these methods are summarized in Table 6.3. Examples of these sample collection devices are illustrated in Fig. 6.15 and 6.16. Details of these sampling methods are found in the references noted in Table 6.3 and in Fig. 6.15 and 6.16.

Suction lysimeters allow the repeated collection of porewater samples from specific locations in the unsaturated zone. A suction lysimeter consists of a vacuum cylinder with a water saturated, slightly pervious plastic or ceramic intake. Water in the lysimeter intake contacts the porewater in the unsaturated zone so that when the lysimeter cylinder is placed under a vacuum slightly in excess of the soil suction, water flows slowly into the lysimeter. Depending on the soil, sample collection times may be as long as several days. For sample collection, the lysimeter is pressurized to force the collected porewater to the surface. Suction lysimeters are not, however, always reliable due to difficulties in maintaining an adequate vacuum in low hydraulic conductivity soils. In addition, the vacuum conditions and the long collection periods can result in considerable changes in porewater chemistry prior to sample recovery.

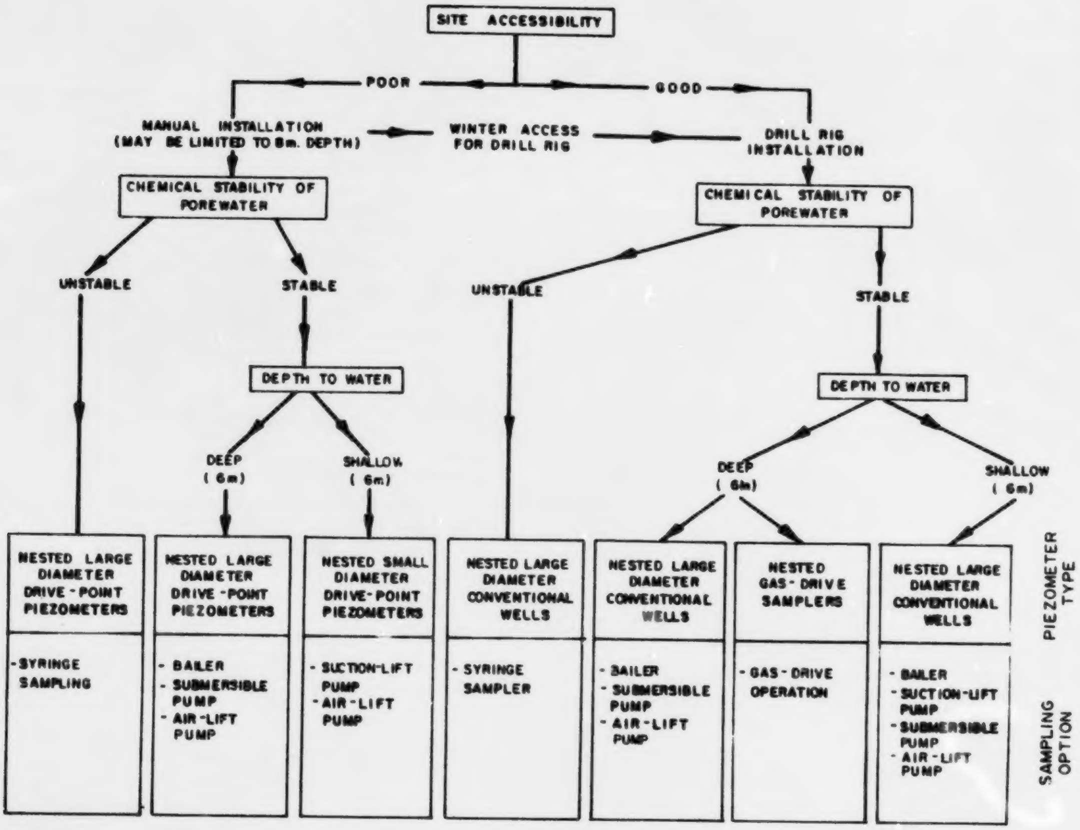

SITE ACCESSIBILITY
POOR
GOOD
MANUAL INSTALLATION (MAY BE LIMITED TO 6m. DEPTH)
WINTER ACCESS FOR DRILL RIG
DRILL RIG INSTALLATION
CHEMICAL STABILITY OF POREWATER
CHEMICAL STABILITY OF POREWATER
UNSTABLE
STABLE
UNSTABLE
STABLE
DEPTH TO WATER
DEPTH TO WATER
DEEP (6m)
SHALLOW (6m)
DEEP (6m)
SHALLOW (6m)
NESTED LARGE DIAMETER DRIVE-POINT PIEZOMETERS
NESTED LARGE DIAMETER DRIVE-POINT PIEZOMETERS
NESTED SMALL DIAMETER DRIVE-POINT PIEZOMETERS
NESTED LARGE DIAMETER CONVENTIONAL WELLS
NESTED LARGE DIAMETER CONVENTIONAL WELLS
NESTED GAS-DRIVE SAMPLERS
NESTED LARGE DIAMETER CONVENTIONAL WELLS
PIEZOMETER TYPE
- SYRINGE SAMPLING
- BAILER
- SUBMERSIBLE PUMP
- AIR-LIFT PUMP
- SUCTION-LIFT PUMP
- AIR-LIFT PUMP
- SYRINGE SAMPLER
- BAILER
- SUBMERSIBLE PUMP
- AIR-LIFT PUMP
- GAS-DRIVE OPERATION
- BAILER
- SUCTION-LIFT PUMP
- SUBMERSIBLE PUMP
- AIR-LIFT PUMP
SAMPLING OPTION

Fig. 6.14 – Selection of piezometer type and porewater sampling method

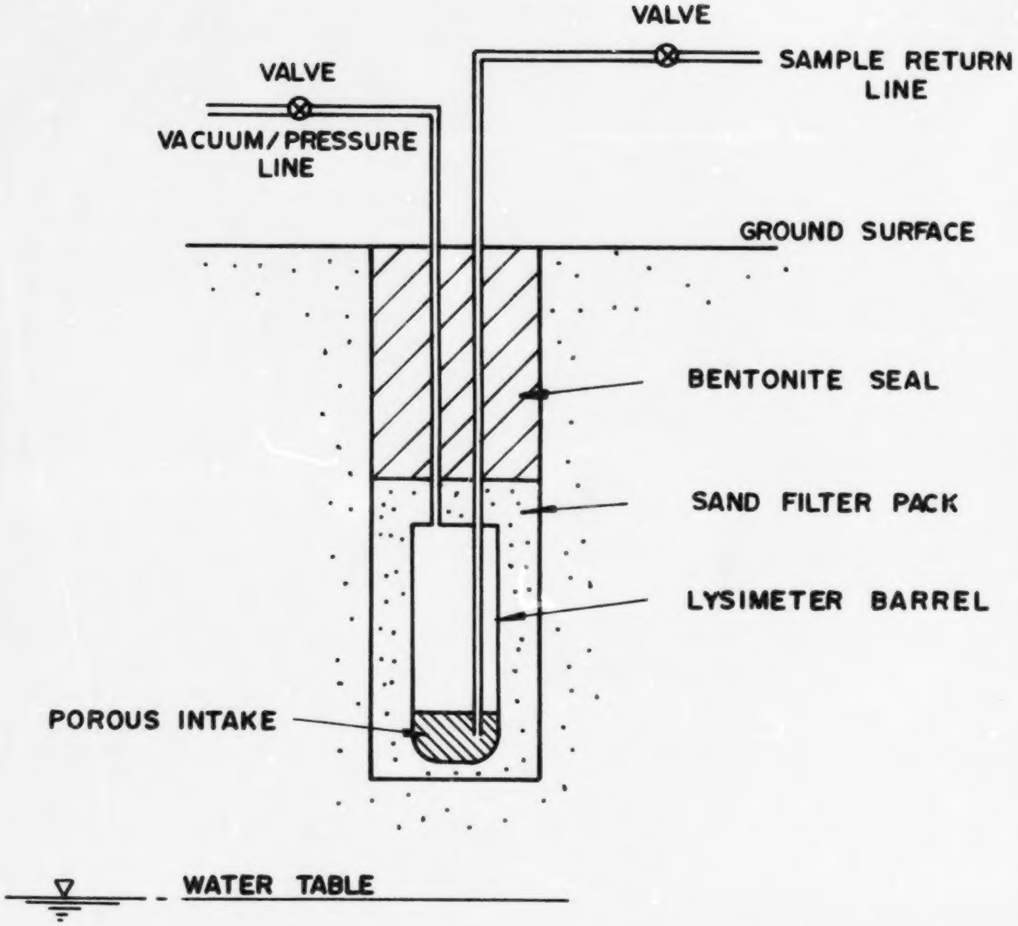
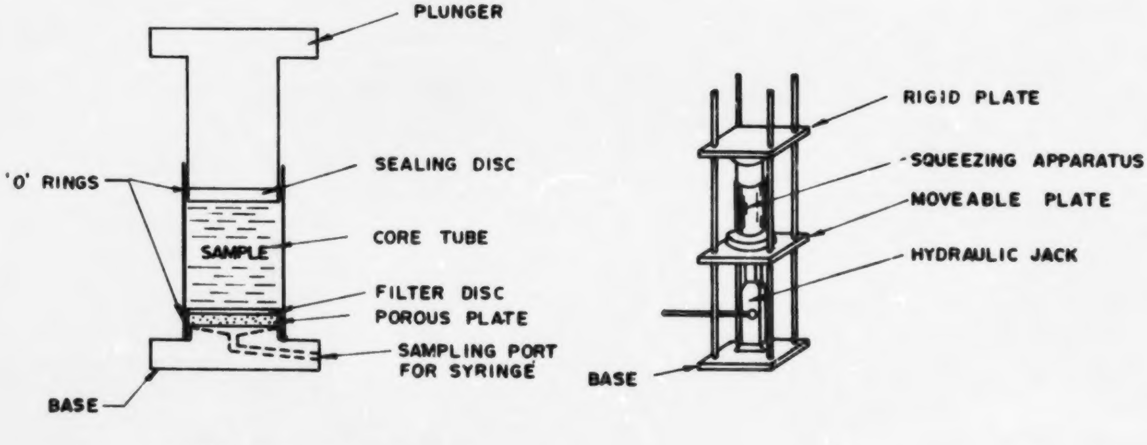

VALVE
VALVE
SAMPLE RETURN LINE
VACUUM/PRESSURE LINE
GROUND SURFACE
BENTONITE SEAL
SAND FILTER PACK
LYSIMETER BARREL
POROUS INTAKE
WATER TABLE

Fig. 6.15 – Suction lysimeter for porewater sampling above the water table


PLUNGER
'O' RINGS
SEALING DISC
SAMPLE
CORE TUBE
FILTER DISC
POROUS PLATE
SAMPLING PORT FOR SYRINGE
BASE
RIGID PLATE
SQUEEZING APPARATUS
MOVEABLE PLATE
HYDRAULIC JACK
BASE

SQUEEZING APPARATUS

STAND

Fig. 6.16 – Tailings core squeezing apparatus for collection of porewater from tailings samples

Coring-squeezing methods allow the collection of less disturbed tailings porewater samples from tailings cores from the unsaturated zone. This method does not allow repeated monitoring of samples from a specific location as would the use of a suction lysimeter. The coring-squeezing method involves the collection of tailings core samples from the unsaturated zone using a Shelby-tube or similar thin-wall tube sampler which will allow the collection of well-sealed samples (see Section 4.3.3). The tailings core samples are then placed in a hydraulic jack squeezing apparatus to remove the porewater. Fine-grained silty tailings samples are simply squeezed and the porewater is released due to consolidation of the sample. The porewater passes through a filter membrane at the bottom of the sample and is collected in a plastic syringe. Porewater from coarse-grained sandy tailings is removed by immiscible displacement because squeezing and consolidation is ineffective. Paraplex, an immiscible organic fluid, is injected and squeezed into the top of the core sample and the sample porewater is released by displacement. The porewater sample is collected in the same manner. This innovative technique has been used successfully in investigations of pyrite oxidation in the unsaturated zone of the Nordic tailings impoundment at Elliot Lake (Smyth, 1981).

6.6.3 Sample Handling and Preservation Methods

The considerations for the handling and preservation of tailings porewater samples are comparable to those for the handling and collection of surface water samples. The guidelines for sample containers, preservation and storage time shown in Table 5.2 are also applicable to tailings porewater samples. Tailings porewater samples are, however, generally more chemically unstable than surface water samples and the need for proper sample preservation in the field immediately upon collection is important.

In addition, unlike surface water samples, all tailings porewater samples must be filtered prior to preservation. Tailings porewater samples collected from piezometers or squeezed from tailings cores often contain small amounts of suspended tailings solids. This suspended material does not represent material that is dissolved in the tailings porewater and consequently must be removed by filtration. Groundwater samples are normally filtered through 0.45 μm membranes prior to preservation and analysis (Gillham et al., 1983).

Tailings porewater samples can be filtered down-the-hole using the syringe sampler (see Fig. 6.11) with a 25 mm diameter filter holder. Tailings porewater samples collected using suction-lift or submersible pumps can be filtered in-line using standard-size 47 mm diameter filter holders or 142 mm filter holders for large volume samples. An example of a 142 mm filter holder is shown in Fig. 6.17. All of the noted filter holders consist of a filter membrane in a lucite or polycarbonate holder. The filter membrane is replaced after each sample to avoid cross-contamination of the samples. The operation of cleaning the filter holder and replacing the filter membrane in the field can often be difficult and time-consuming. To avoid replacing and cleaning filters in the field, and to eliminate potential cross-contamination, self-contained disposable filter cartridges are available but they are considerably more costly.

6.6.4 Analytical Methods

As with surface water samples, parameters such as pH, electrical conductance, temperature and dissolved oxygen should be analysed in the field immediately following collection. Field measurement of these parameters is particularly important for tailings porewater because samples with high concentrations of ferrous iron may oxidize rapidly with the consequent decrease in sample pH and precipitation of ferric hydroxide. Detailed procedures for these measurements are referenced in Section 5.3.2.4.

The analysis of tailings porewater samples can be conducted using the same methods used for the analysis of other waters and wastewaters. Standard methods for the analysis of chemical and radiological parameters are described by Environment Canada

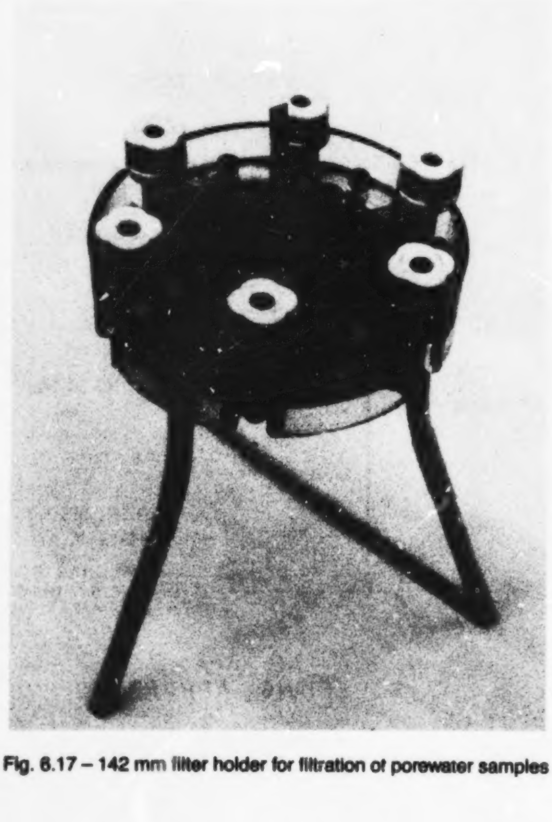


Fig. 6.17 – 142 mm filter holder for filtration of porewater samples

(1979), Environment Ontario (1981), the American Public Health Association (1980), the U.S. Department of the Interior (1977), and ASTM (1983) Volume 11.01.

6.7 QUALITY ASSURANCE FOR POREWATER SAMPLING

The general quality assurance considerations for tailings porewater sampling are comparable to those described in Section 5.5 for surface water sampling. The accurate and comprehensive recording of field data is a vital component of a porewater sampling program. Field data from a sampling program will include sample identification numbers, sampling locations, information on sampling methods, field measurements and the numbers and types of samples collected for laboratory analyses. Field data such as these are best recorded on prepared sampling forms to ensure that all pertinent observations are made and the information is recorded in a standard manner. An example of a porewater (groundwater) sampling form is shown in Fig. 6.18.

Quality control procedures such as the use of field blanks and field standards (see Section 5.5.2) are applicable to tailings porewater sampling programs to evaluate possible errors resulting from field sampling procedures. Field duplicate samples can be used to check the precision or reproducibility of the laboratory chemical analyses.

Methods such as ionic balance calculations and the examination of EC-TDS, EC-ionic sum and summed TDS-measured TDS relationships can be used to assess the general reliability/completeness of major ion chemical analyses. These methods are outlined in Section 5.5.3.

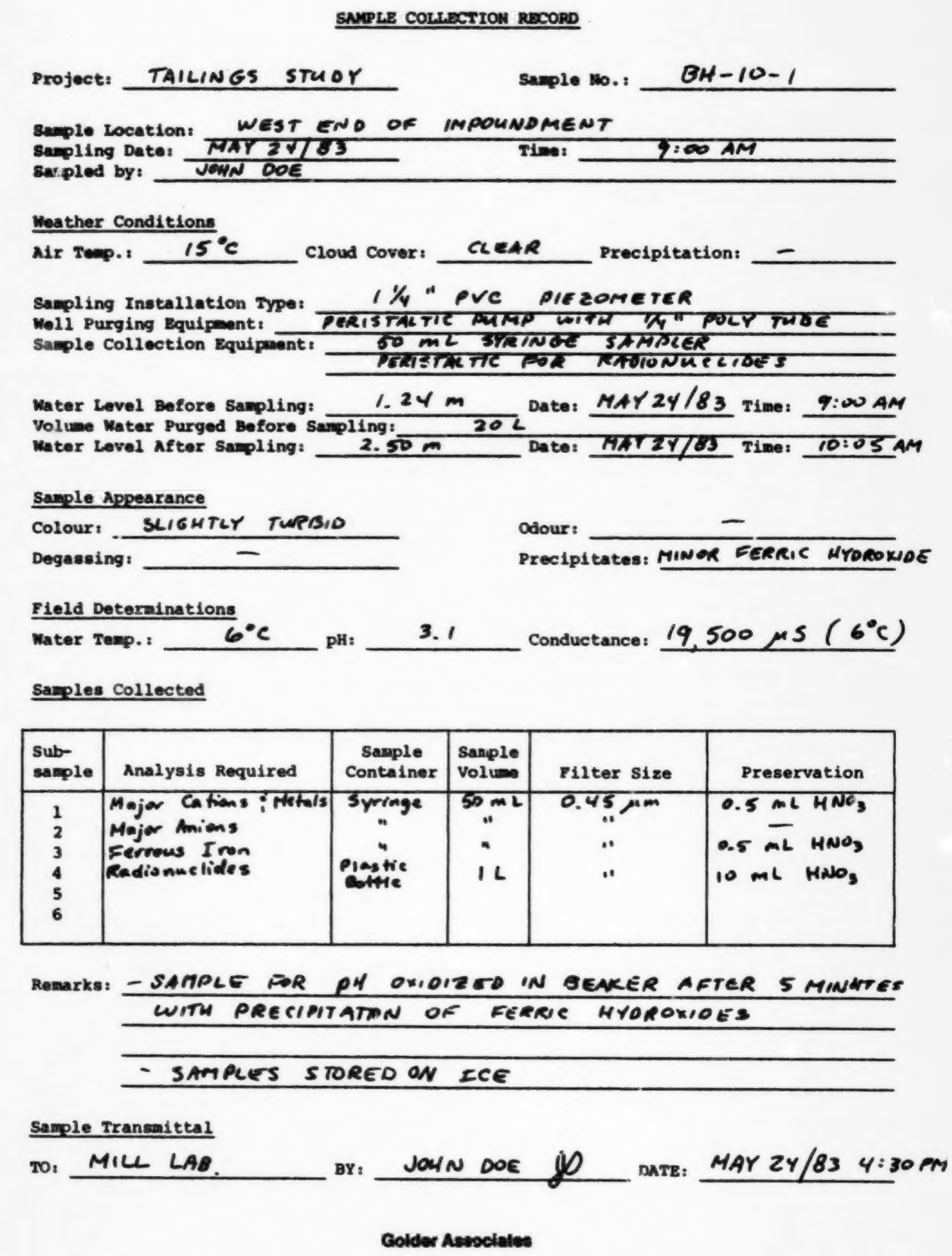
6.8 PROGRAM COSTS

The cost of a tailings porewater sampling program will depend on the type and number of piezometer installations and the number of individual samples. The following are generalized unit cost estimates for key aspects of a tailings porewater sampling program, which can be used to develop overall program costs.

The cost of materials for piezometer installations increases as the diameter of the piezometer increases. For example, the materials for polyethylene bundle piezometers or PVC piezometers less than 5 cm in diameter would range from $5 to $10 per metre, while PVC piezometers 5 to 15 cm in diameter would range from $10 to $35 per metre in 1984. Piezometers can be installed either manually for shallow depths of less than 8 m, or with a drill rig. Manual installation methods for piezometers typically allow completion of 4 to 8 metres of piezometer installation per hour for a two person field crew. Piezometers installed using a drill rig are generally associated with drilling for a tailings solids sampling program. Typical drilling advance rates range from 1 to 4 metres per hour depending on the tailings solids sampling methods used (see Section 4.7).

The sampling of porewater from piezometer installations is considerably more involved and time consuming than surface water sampling. Porewater sampling procedures will include purging of the piezometers, sample collection, field measurements, sample filtration, sample preservation and a rising-head permeability test. From 3 to 6 porewater samples can typically be collected per day by a single field person.

Piezometer installation and porewater sampling generally require experienced specialized field personnel to supervise drilling operations and construction of the piezometers, accurately record field observations and measurements, and collect the porewater samples. Typical consultants rates for such specialized personnel range from $35 to $50 per hour for engineers/hydrogeologists in 1984.



SAMPLE COLLECTION RECORD

Project: TAILINGS STUDY　Sample No.: BH-10-1

Sample Location: WEST END OF IMPOUNDMENT
Sampling Date: MAY 24/83　Time: 9:00 AM
Sampled by: JOHN DOE

Weather Conditions

Air Temp.: 15°C　Cloud Cover: CLEAR　Precipitation: —

Sampling Installation Type: 1 1/4 " PVC PIEZOMETER
Well Purging Equipment: PERISTALTIC PUMP WITH 1/4" POLY TUBE
Sample Collection Equipment: 50 mL SYRINGE SAMPLER
PERISTALTIC FOR RADIONUCLIDES

Water Level Before Sampling: 1.24 m　Date: MAY 24/83　Time: 9:00 AM
Volume Water Purged Before Sampling: 20 L
Water Level After Sampling: 2.50 m　Date: MAY 24/83　Time: 10:05 AM

Sample Appearance

Colour: SLIGHTLY TURBID　Odour: —
Degassing: —　Precipitates: MINOR FERRIC HYDROXIDE

Field Determinations

Water Temp.: 6°C　pH: 3.1　Conductance: 19,500 µS (6°C)

Samples Collected

Sub-sample	Analysis Required	Sample Container	Sample Volume	Filter Size	Preservation
1	Major Cations ; Metals	Syringe	50 mL	0.45 µm	0.5 mL HNO_3
2	Major Anions	"	"	"	—
3	Ferrous Iron	"	"	"	0.5 mL HNO_3
4	Radionuclides	Plastic Bottle	1 L	"	10 mL HNO_3
5					
6					

Remarks: - SAMPLE FOR pH OXIDIZED IN BEAKER AFTER 5 MINUTES WITH PRECIPITATION OF FERRIC HYDROXIDES

- SAMPLES STORED ON ICE

Sample Transmittal

TO: MILL LAB.　BY: JOHN DOE JD　DATE: MAY 24/83 4:30 PM

Golder Associates

Fig. 6.18 – Example of porewater (groundwater) sampling form

6.9 REFERENCES

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7. WIND-BLOWN DUST AND RADON

7.1 OBJECTIVES

Airborne emissions from tailings impoundments are generally in the form of wind-blown dust and/or radon gas. The concern with the wind-blown dust lies with the particulate radionuclides which constitute the prime sources of inhaled radioactivity. Most particulate radionuclides are members of the uranium-238 decay series. However, where natural thorium is present, members of the thorium-232 decay series may also be present. The radioactive decay schemes for these two natural elements are summarized in Appendix A.

Two commonly used measurements in the assessment of air quality are dustfall and suspended particulate matter concentrations. Both measurements provide the data necessary to characterize the wind-blown tailings dust in terms of quantity and chemical/radiological composition. Sampling techniques for dustfall and suspended particulate matter are discussed in Section 7.3.

Radon, the gaseous member of the uranium-238 decay chain, and thoron, the gaseous member of the thorium-232 decay chain (where thorium-232 is present) are two additional radioactive emissions of interest. In most situations radon is of much greater concern than thoron, hence the following discussions focus on radon. Measurements of radon concentrations in the air surrounding a tailings impoundment are important in the assessment of existing conditions and dose estimates associated with such tailings impoundments. To complement the assessment of ambient conditions, measurements of the rate of radon emanating from the surface of the tailings may be carried out to assess the ambient radon potential of the site and provide information on how alternative decommissioning strategies may affect radon release rates. Sampling techniques for ambient radon and radon flux measurements are discussed in Section 7.4.

7.2 SELECTION OF SAMPLING LOCATIONS

The quantities of radon and wind-blown dust originating from a tailings impoundment are affected by many factors, including wind speed, atmospheric stability, rainfall, wind direction, barometric pressures, topography, vegetative cover, freezing conditions and snow coverage. It is important, therefore, in the selection of the monitoring locations, to take account of as many of these factors as possible. The selection of sampling locations for air quality monitoring is described in ASTM (1983) Volume 11.03: D1357-82.

The amount of particulate radionuclides (dust) picked up from the surface of a tailings impoundment and transported by winds is dependent largely upon the condition of the tailings surface and the speed and direction of the dominant winds. Consequently, the most important sampling sites are generally located downwind and upwind of the tailings impoundment as illustrated in Fig. 7.1.

The presence or absence of vegetative covering on the tailings also affects dust generation rates. For example, the presence of a stable vegetative cover will substantially reduce dust generation rates (C.D.O.H., 1981). Local wind fields will also be affected by the nature and type of vegetation on the tailings or adjoining lands (e.g., forest cover versus grasslands).

Two other factors which must be considered in the selection of sampling sites are surface topography and land use. Gently rolling or flat terrain generally presents relatively few problems in terms of wind funnelling and wind field alteration. However, in other settings the presence of large hills or valleys or large water bodies may affect site-specific wind patterns. Such local geomorphic features must be assessed on a site-specific basis in order to develop the most appropriate sampling location configuration.

Land use in the area surrounding the tailings is another feature which must be taken into account during the selection of the sampling locations. The type of land use (industrial, residential, etc.) and extent of the development in an area surrounding tailings can influence the air quality and make the assessment of the tailings contribution difficult. Materials-handling operations and roadways in the vicinity of the tailings are two such examples of land use which may influence the air quality.

To quantify the effect of land useage on air quality, additional off-site sampling stations may be required. Figure 7.2 depicts an example of how local land use could affect interpretation of the air quality data.

Such considerations suggest that to the extent practicable, a sampling grid pattern spatially oriented around the tailings be used to assess both the magnitude and extent of the contaminant plume. Such a grid would be oriented with the major emphasis downwind (based on the predominant wind direction) of the tailings area; however, sample points should also be located (where possible) upwind of the tailings site and along the axes as implied by the general shape of the area. Figures 7.1 and 7.2 depict hypothetical sampling configurations for flat terrain tailings areas.

Another important consideration, often overlooked in the initial selection of sampling locations, is the availability of electrical power to operate high volume samplers. The motors in these sampling units must be able to operate continuously for 24-hour periods with input voltages ranging from 110 to 120 volts, 50-60 Hz and must have a third wire safety ground. Battery-operated low volume air sampling systems

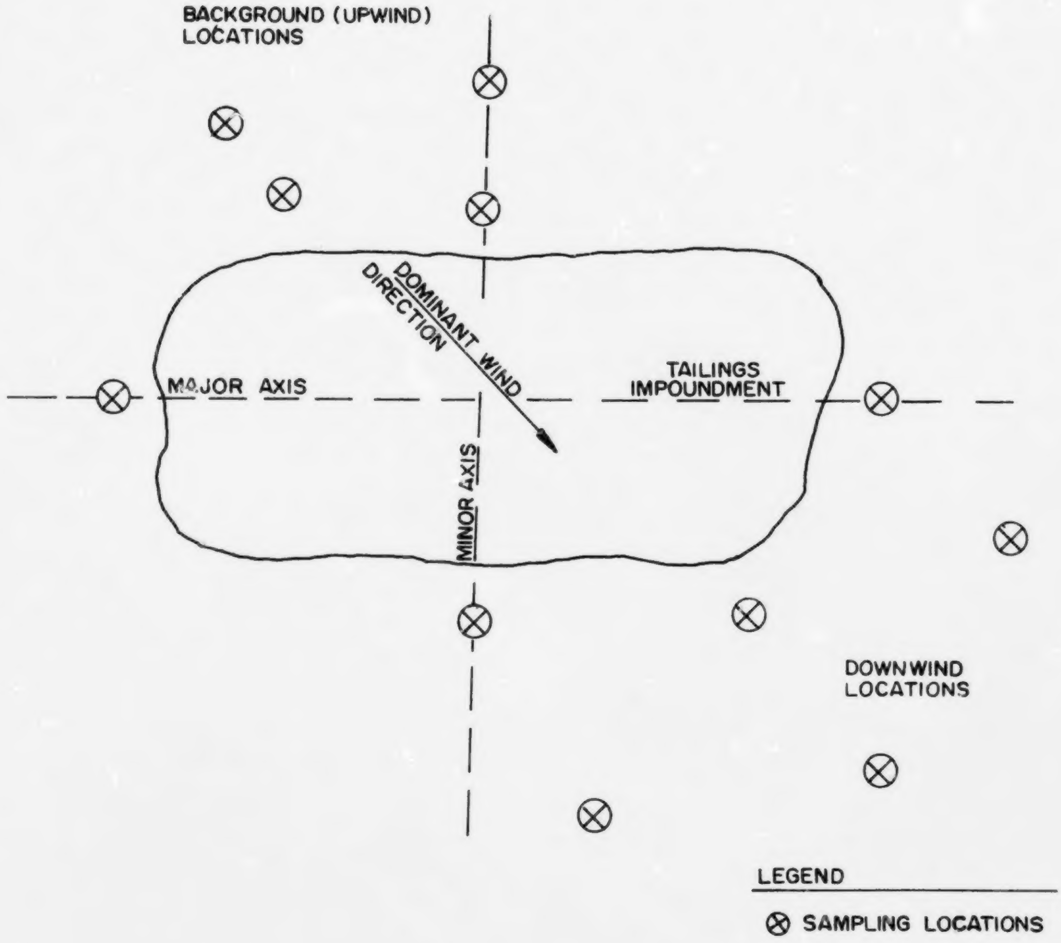


Fig. 7.1 – Selection of sampling locations for wind-blown dust

are available for use in circumstances where 110 volt power is not available. In addition, electrical power can be provided from gasoline or diesel generator sets. However, it should be noted that experience suggests such generator sets are particularly vulnerable to vandalism.

The amount of radon gas diffusing from tailings depends on several factors. The release rate has been shown to vary by more than a factor of 10 due to the effects of weather, e.g., changes in barometric pressure, atmospheric stability, rainfall, changes in wind speed and snow cover (e.g., Swift et al., 1976). On this basis, therefore, the selection of the radon sampling locations would follow an evaluation process similar to that for the airborne dust samples.

7.3 WIND-BLOWN DUST

7.3.1. Parameters

The two parameters measured are suspended particulate matter and dustfall. Suspended particulate matter refers to the wind-blown dust particles having diameters of less than 100 μm, (Stokes equivalent), which are drawn into a covered housing and collected on a filter surface. More commonly the phrase refers to dust particles less than about 44 μm in size (Environment Ontario, 1981). Dustfall is a measure of the settleable particulates from the atmosphere and includes all materials which will pass through a 20-mesh-size screen.

As noted in Section 7.2 many factors can affect the levels of dustfall and suspended particulate matter. These factors can be divided into two basic types, namely physical and chemical/mineralogical. Meteorological conditions such as wind speed and direction, precipitation, soil temperature, duration of snow cover, etc., are important factors influencing the extent and seasonal variation of air quality for the tailings impoundment environs.

Although high winds are typically associated with high dust levels the situation may arise when the ground is frozen, saturated (following a rain storm) or

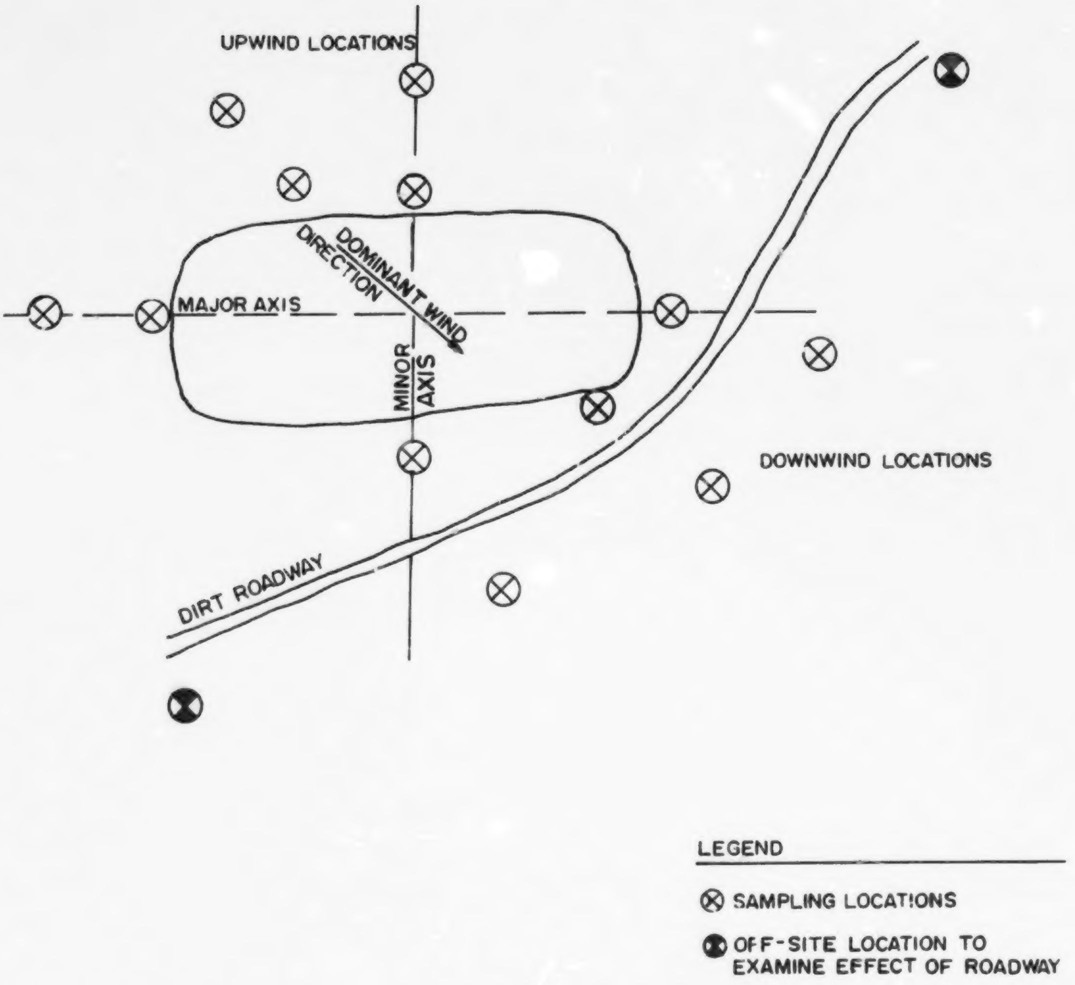


Fig. 7.2 – Selection of sampling locations for wind-blown dust with land-use effect

covered with snow, thereby greatly inhibiting the dust generation rate. Conversely a saturated soil condition could be 'dried up' by continued high winds thereby increasing the dust generation rate.

Physical characteristics of the tailings solids such as particle size, moisture content and density are important factors in determining the aerodynamic properties of the wind-blown dust. The tailings solids size distribution also plays an important role in determining the downwind concentrations. The mechanisms by which tailings are moved by wind are similar to the movement of sand and soil. Bagnold (1959) considered three types of particle transport: saltation (bouncing), creep (rolling), and suspension. The wind causes large particles, which have a relatively large aerodynamic drag, to bounce or roll across the tailings surface. The impact of large particles on the smaller tailings particles is the actual source of suspended material. The larger airborne particles (in the order of 40-80 μm in diameter) are quickly brought to the ground by gravity. The smaller suspended dust particles (less than about 40 μm in diameter) can be carried by the air currents for substantial distances.

The chemical/mineralogical characteristics of the tailings solids are important not so much in terms of generation rates but in terms of the assessment of the potential environmental or health concerns associated with the wind-blown dust levels.

7.3.2 Sample Collection Methods

High volume air samplers have been used extensively for about three decades to determine concentrations of total suspended particulate material. The high volume sampler is a device that draws a known volume of ambient air through a filter with a high flowrate blower within a measured time interval. A typical high volume sampler is shown in Fig. 7.3. To determine the concentrations (e.g., gravimetric), chemical, or other characteristics of the particulate on the filter, three independent determinations must be made, namely: mass of particles; volume flowrate of ambient air through the filter; and the sampling time. All three must be measured with sufficient accuracy to give the required accuracy in the calculated result. Typical examples of suitable accuracies are mass to the nearest milligram; flowrate to the nearest 0.03 cubic metre per minute; and time to the nearest two minutes (Alberta Environment, 1977).

Fig. 7.3 – High volume air sampler for determination of suspended particulate

Suspended particulate sampling is commonly carried out for a 24-hour period, from midnight to midnight, with samples taken every 6th day to correspond with the National Air Pollution Surveillance network (NAPS) sampling schedule. However, variations in sampling duration and frequency may be incorporated into the specific program as required i.e., heavy dust loadings may require reduction in the sampling duration to 6 or 8 hours. Alternatively, samplers may be run continuously to obtain a sufficiently large sample for chemical/radiological analysis.

The detailed sampling method is outlined by Environment Canada in "Standard Reference Method for the Measurement of Suspended Particulate in the Atmosphere (High Volume Method)" and in ASTM (1983) Volume 11.03: D4096-83.

The standard high volume air sampler can collect particles up to 100 μm in size but is not capable of separating them into particulate size ranges. The amount of dust present in the respirable size range can also be important. As a result of this interest in the respirable fraction of suspended particulate matter, several types of high volume samplers have been designed specifically to measure smaller particle size fractions. The dichotomous sampler or virtual impactor, and the size selective inlet are two examples of such devices. Specific reference must be made to suppliers' data sheets for information on particle size ranges and collection efficiencies for such detectors. The greater costs for such units compared to high volume samplers have limited their widespread use in the air monitoring field. Despite this problem and the need to consider newer suspended-particulate measurement techniques, the use of the traditional high volume sampler is a widely recognized and long-used method (Nicholas and Visalli, 1981) and will probably continue to provide the basic data in this field.

For dustfall sampling, an open topped cylinder with a flat bottom, of a specified size and shape (typically 152 mm diameter and 457 mm deep) is supported above the ground and left open to collect settleable particulate matter over a 30-day period. A typical configuration is shown in Fig. 7.4. Since these dustfall jars are passive collectors and do not require any electrical power, the selection of a suitable sampling location is less restrictive than that for the high volume sampler. However, the dustfall jar should be located with a clear field of exposure, free of interference from buildings or other high objects. The top of the jar should be a minimum of 2.5 m and a maximum of 15 m above any other surface in the immediate vicinity. Procedures for the collection of dustfall samples are described in ASTM Volume 11.03: D1739-82.

The dustfall jar should be left for a 30-day exposure after which it should be removed and replaced with a clean jar. (In certain situations a longer exposure may be desirable). Following removal, the jar should be capped and sealed to prevent any loss or leakage of the contents during shipping to the laboratory.

For areas where the sample volume may be too small to carry out the required analyses, the number of jars at each location may be doubled. If this double jar procedure results in insufficient sample volume, then multiple monthly composite samples may be required. Review of initial data will aid in the selection of the appropriate sampling scenario.

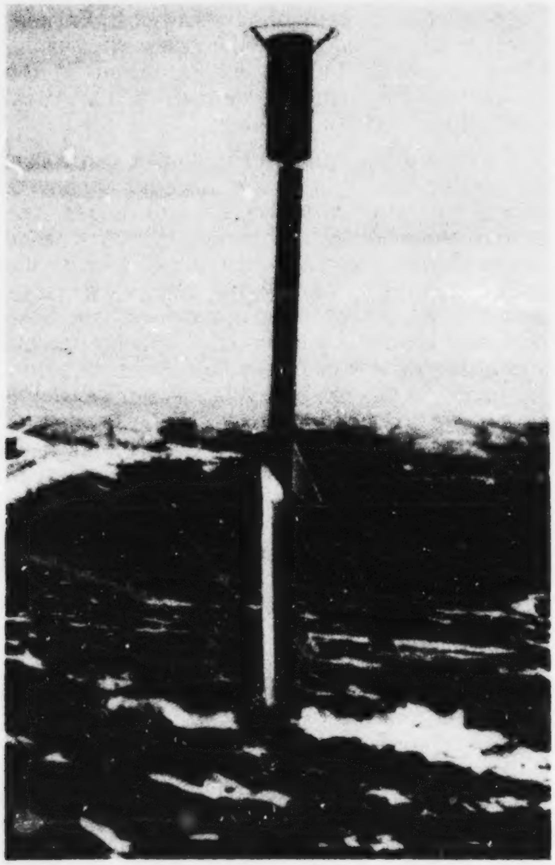


Fig. 7.4 – Dustfall sampler

7.3.3 Analytical Methods

At the end of the sampling period, the exposed filter from the high volume air sampler should be carefully removed, folded in such a manner that sample touches sample, and placed in the appropriately labelled envelope for shipment to the laboratory. At the laboratory, the samples should be dried and weighed to determine the total suspended particulate matter concentration (SPM). Once the total SPM has been determined the filter may be cut into portions (typically 1/4) to form a monthly (or longer time) composite for analysis of various components such as radionuclides and metals. For more detailed information on the analysis techniques, the laboratory(ies) carrying out the sample analysis should be consulted. Particular attention should be given to the lower limit of detection and the coefficient of variation (or equivalent) quoted by the selected laboratory for the required analyses. Samples should also be selected for inter-laboratory comparisons.

Following a 30-day exposure period the dustfall jars are sent to the lab for analysis of total and total fixed dustfall. The terms 'total dustfall' and 'total fixed dustfall' are defined as the amount of material left after evaporation of a sample of dustfall in water and its subsequent drying in an oven at 103°-105°C for one hour, and igniting at 550°C for 30 minutes. The total dustfall includes both suspended and dissolved matter. The total fixed dustfall is the portion of the total dustfall remaining after ignition. The loss in weight is mainly due to combustion of organic matter.

Once the total dustfall analysis has been completed, additional testing may be carried out on the dustfall for various components including heavy metals and radionuclides as discussed for SPM.

7.4 RADON

7.4.1 Parameters

Radon-222 will be released from tailings surfaces for as long as the radium-226 parent (half-life 1620y) is present. Radium concentrations in uranium tailings are typically in the order of 10 to 20 Bq/g of tailings. However, only a fraction of the radon produced through the natural decay of radium in the tailings mass is released from the surface of the tailings. One of the most important factors in determining this mass material release is the fraction of radon that escapes from the solid tailings particles and is free to diffuse (emanation fraction). Experiments have shown that a 15-25% radon emanation fraction applies to many tailings areas (USNRC, 1980; Chambers et al., 1980). When all factors are considered, in effect only the radon produced in the top 1-2 m of tailings can potentially escape to the atmosphere (Swift et al., 1976).

As discussed earlier, the rate at which radon diffuses from the surface of tailings depends on many factors. The release rate has been shown to vary by 10 times or more due to the effects of weather e.g., changes in barometric pressure, atmosphere stability, rainfall, changes in wind speed and the presence of freezing conditions or snow cover. As an example, exhalation rates measured during the summer of 1977 at Elliot Lake tailings areas ranged from 0.33 to 70.6 Bq/m^2/s (James F. MacLaren Ltd., 1978).

In addition, the water content of the tailings also affects the radon diffusion rate. Theoretical calculations indicate that water saturated tailings will reduce radon diffusion by a factor of ten or more as compared with dry tailings. Awareness of these many factors and their influence on radon diffusion is essential in the design and operation of successful radon and radon daughter monitoring programs.

While radon daughter concentration is the important factor in health assessment, measurement of radon concentration provides the most convenient measure of release rate from tailings and its effect on local air quality.

7.4.2 Radon Exhalation Measurements

Radon gas exhalation rates from tailings surfaces are easily measured by an in situ accumulation method. For this procedure a container of suitable size (typically 25 litres) is placed with the open end on the surface of the tailings and the increase in concentration of radon in the container is measured with time. A typical radon flux sampler is shown in Fig. 7.5. By measuring the concentration of radon released into the drum with time, the rate of exhalation can be calculated. A detailed description of this method is found in Bernhard et al. (1975).

Other techniques such as the charcoal cannister technique described by Countess (1977) have also been used to determine radon flux. Recently, application of this technique to uranium tailings has been described by Silker and Heasler (1979).

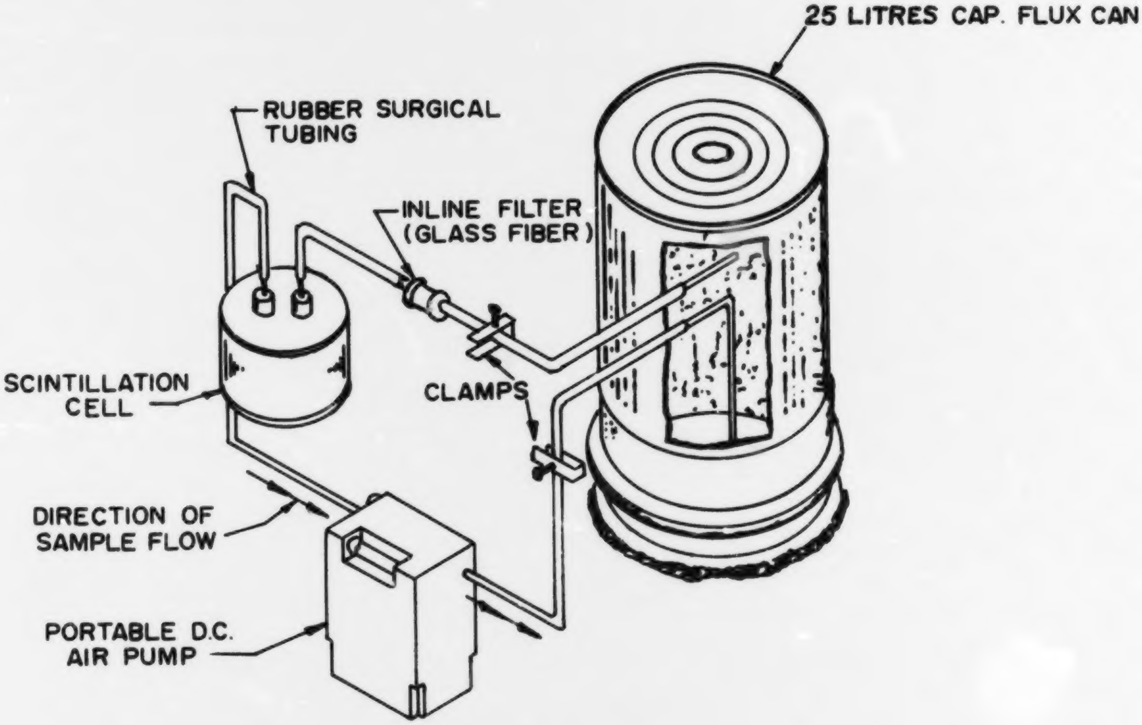

25 LITRES CAP. FLUX CAN
RUBBER SURGICAL TUBING
INLINE FILTER (GLASS FIBER)
SCINTILLATION CELL
CLAMPS
DIRECTION OF SAMPLE FLOW
PORTABLE D.C. AIR PUMP

Fig. 7.5 – Apparatus for measurement of radon flux from tailings surface

7.4.3 In Situ Radon Measurements

Where tailings are sufficiently dry, radon gas concentrations can be measured at various tailings depths to determine the average radon driving force for the specific tailings. The typical approach is to place detectors (or take measurements) at specified depths in a tailings impoundment in order to measure radon concentration versus depth. These data provide a direct measurement of the diffusion properties of the tailings material. Application of track etch techniques to radon flux measurement has been described by Fleischer (1980). The installation of solid-state radon gas probes in tailings and radon measurement has been described in detail by Bigu et al. (1982).

7.4.4 Ambient Air Monitoring

Both ambient radon and radon daughter concentrations are important in assessing potential doses to man. Ambient radon can be measured in several ways including time averaged measurement through the use of passive monitors or by taking instantaneous or grab samples. The passive method involves the use of nuclear track etch detectors to measure the average (time integrated) ambient radon concentration (typically over exposure periods of several weeks or even months). The grab sample method involves the use of high and low volume pumps, filters, scintillation cells and photomultiplier-scaler assemblies to determine the actual radon and radon daughter concentrations at the time of sampling. Instantaneous radon and radon daughter measuring devices are also commercially available.

Typically the track etch detector film is mounted in the bottom of a light plastic cup. A filter material is affixed to the mouth of the cup to prevent entry of radon daughters and dust, and the cup is installed in a protective all-weather shelter at the sampling location.

Once the specified sampling duration has been attained, the cup/detector assembly is removed from the shelter and sent for analysis. Such a passive system is only capable of measuring the average radon or thoron concentration over the specified time period.

For the radon grab sample techniques, a filtered air sample is drawn through a scintillation cell for a specified period of time at a sufficient flowrate to allow at least 10 air changes in the cell. After a suitable delay period to permit the ingrowth of radon daughters, the scintillations produced by the decaying radon/radon daughters are counted and converted to a radon concentration using the calibration factors supplied by the manufacturer.

For the radon daughter sampling technique a calibrated high volume pump (30 L/min) is used to draw air through a filter of 0.45 μm porosity for a specified period of time (5-10 minutes). Radon daughter concentrations are typically determined following the modified Kusnetz method (IAEA, 1976) which consists of counting the alpha-emitting radon daughters that are deposited on a filter by removal from a known volume of air. In recent years, several manufacturers have offered continuous radon and working level monitors to the commercial market. The reader is referred to the suppliers' literature for specific details.

7.5 QUALITY ASSURANCE

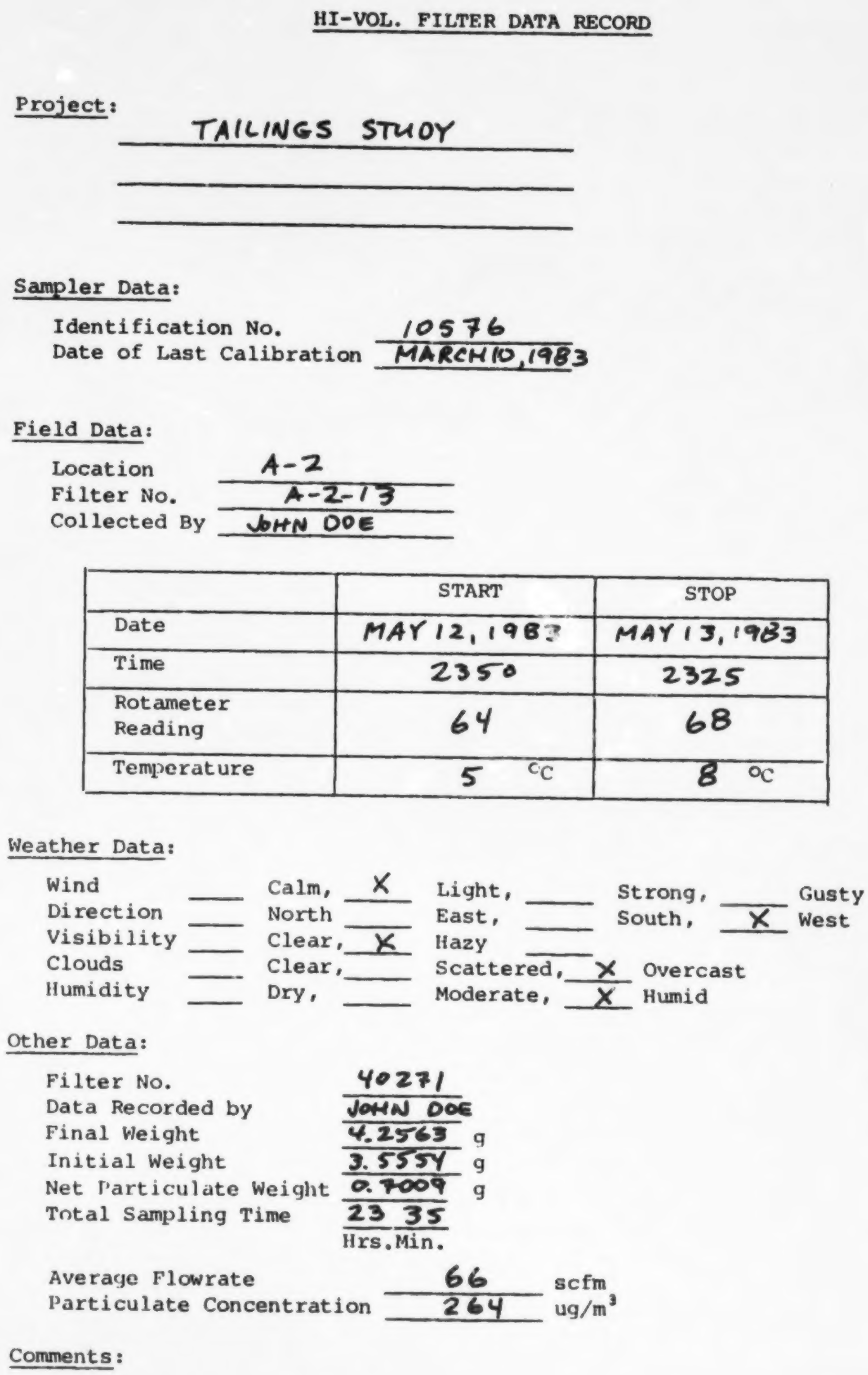
The accurate and comprehensive recording of field data and sampling procedures is a vital component of an air quality monitoring program. Field data and sampling information will include: sample identification numbers; sample locations; period of sampler operation; general weather conditions and specific weather incidents (high winds, heavy rain, etc.); and instrument calibration data. This type of information is best recorded on prepared field data collection forms to ensure that all pertinent observations are made and the data recorded in a standardized manner. An example of a sample collection form for a high volume air sampler is shown in Fig. 7.6.

Recalibration of a high volume sampler is required at least twice a year and after every motor and brush change to maintain air volume accuracy. The brushes of the sampler should be checked on a regular basis, and generally require replacement every 400-500 hours of operating time. It is recommended that the owner's manual be consulted for specific calibration and servicing instructions.

7.6 PROGRAM COSTS

The major cost of air quality sampling programs at uranium tailings impoundments involves the acquisition and initial set-up of the monitoring instrumentation. The following are generalized unit cost estimates which can be used to develop overall program costs.

The cost for the acquisition and initial set-up of a typical high volume suspended particulates air sampler by qualified field personnel would be approximately $2,500 to $3,500 per sampler in 1984. The cost for the acquisition and set-up of typical dustfall collectors would be approximately $200 per sampler in 1984. The cost of materials for ambient radon measurements using track-etch cups would be approximately $150 to $200 per measurement in 1984. The cost of acquisition of equipment for radon flux measurements is approximately $5,000 to $6,000 with an operating cost of approximately $200 per measurement in 1984.



HI-VOL. FILTER DATA RECORD

Project:
TAILINGS STUDY

Sampler Data:

Identification No. 10576
Date of Last Calibration MARCH 10, 1983

Field Data:

Location A-2
Filter No. A-2-13
Collected By JOHN DOE

	START	STOP
Date	MAY 12, 1983	MAY 13, 1983
Time	2350	2325
Rotameter Reading	64	68
Temperature	5 °C	8 °C

Weather Data:

Wind ___ Calm, X Light, ___ Strong, ___ Gusty
Direction ___ North ___ East, ___ South, X West
Visibility ___ Clear, X Hazy ___
Clouds ___ Clear, ___ Scattered, X Overcast
Humidity ___ Dry, ___ Moderate, X Humid

Other Data:

Filter No. 40271
Data Recorded by JOHN DOE
Final Weight 4.2563 g
Initial Weight 3.5554 g
Net Particulate Weight 0.7009 g
Total Sampling Time 23 35 Hrs.Min.

Average Flowrate 66 scfm
Particulate Concentration 264 ug/m³

Comments:

Fig. 7.6 – Example of high volume air sampling form (completed for a typical sampling period).

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8. CASE HISTORY – SAMPLING PROGRAMS AT DENISON MINES, ELLIOT LAKE, ONTARIO

8.1 INTRODUCTION

The following case history describes the sampling programs which have been conducted at the Denison Mines Limited Tailings Management Areas at Elliot Lake, Ontario. Information on various aspects of the sampling programs presented in this case history is principally derived from Denison Mines data and reports by La Rocque and Webber (1978), James F. MacLaren Ltd., (1978) and Feenstra et al. (1981).

Denison Mines is located 16 km north of the town of Elliot Lake in Ontario (see Fig. 8.1). Elliot Lake is in a wet temperate climatic region which receives approximately 97 cm of precipitation annually. The precipitation is relatively evenly distributed throughout the year with monthly average precipitation ranging from 5-10 cm. The Elliot Lake area is snow covered from November to April and experiences mean July temperatures of 18°C.

The Denison orebody is a uraniferous quartz-pebble conglomerate, grading approximately 0.1 per cent U_3O_8. The mine and mill operations commenced in 1957 at a design capacity of 5400 tonne/day. The mine-mill capacity was increased to 6400 tonne/day in 1974 and to 13 400 tonne/day in 1982. The uranium is leached from the ore using a strong sulfuric acid solution. Uranium is extracted by strong base ion exchange and precipitated as ammonium diuranate. The barren tailings solids and barren ion exchange solution are neutralized with lime and discharged to the tailings impoundment as a slurry consisting of 30 to 40 per cent solids. The tailings discharge is currently neutralized to a pH of 9 to 10, but during the 1950's and early 1960's was only neutralized to a pH of 6 to 7. From 1957 to 1959, tailings were discharged to the Smith Lake – Williams Lake area to the south of the mill (see Fig. 8.2). Since 1959, tailings have been discharged to Long Lake.

The following case history describes the sampling programs conducted at the inactive Williams Lake tailings impoundment and the currently active Long Lake tailings impoundment.

The tailings discharged to the tailings impoundments contain from 3 to 7 weight per cent pyrite. When the discharge of neutralized tailings ceases and the tailings in the inactive tailings impoundments, such as Williams Lake, are exposed to the atmosphere, pyrite oxidation commences close to the surface of the tailings. Pyrite oxidation produces low pH conditions and high concentrations of iron and sulfate in the tailings porewater. These conditions result in the release of high concentrations of heavy metals and various radionuclides from the tailings solids into the tailings porewater. This poor quality porewater can move out of the tailings impoundments via surface water runoff, seepage or exfiltration and could have unacceptable effects on the surrounding environment. At the present time, these effects are controlled by collection and treatment of contaminated runoff and seepage. Pyrite oxidation is not a significant problem in active tailings impoundments such as Long Lake due to the continual input of neutralized tailings.

8.2 WILLIAMS LAKE TAILINGS IMPOUNDMENT

8.2.1 Introduction

The Williams Lake tailings impoundment covers 10.6 ha and contains approximately 1 million tonnes of tailings. The tailings impoundment is enclosed by bedrock ridges to the north and south, and by Dams No. 1 and No. 2 to the west and east respectively. The bedrock ridges consist of relatively low permeability metamorphosed conglomerates, siltstones and arkoses of the lower Proterozoic Gowganda Formation. The tailings in the central portion of the impoundment are up to 12 m in thickness, and are underlain by thin (<3 m) deposits of glacial till and discontinuous layers of silt and peat. Dam No. 1 is approximately 8 m in height and consists of earthfill. Dam No. 2 is approximately 10 m in height and consists of spigotted tailings. Because tailings were discharged into Williams Lake from Smith Lake, the surface of the tailings slopes from east to west at a grade of approximately 0.5 per cent, and sand tailings predominate in the east end of the impoundment while silty tailings predominate in the west end. During the late 1950's, a failure of the decant system resulted in a spill of tailings down the valley to the west of Williams Lake. This spill area was capped with glacial till and vegetated (Murray et al., 1979). Until 1970, the surface of the tailings impoundment remained relatively dry. The decant structure was raised in 1970 and thus created a headpond which, at times, covers up to half the surface of the tailings impoundment. Remedial works were implemented in 1979 to improve the stability of Dam No. 1 (see Reades et al., 1981).

Since the Williams Lake tailings impoundment was deactivated in 1959, a variety of sampling programs have been implemented for a variety of purposes. These programs have included sampling of tailings solids, surface water runoff, seepage, tailings porewater and wind-blown dust. The sampling of runoff and seepage was conducted as part of Denison Mines routine monitoring program. Wind-blown dust sampling was conducted as part of the 1976-1978 environmental assessment of uranium mining in the Elliot Lake area. The sampling of tailings solids and tailings porewater was conducted as part of a continuing program at Denison Mines directed toward

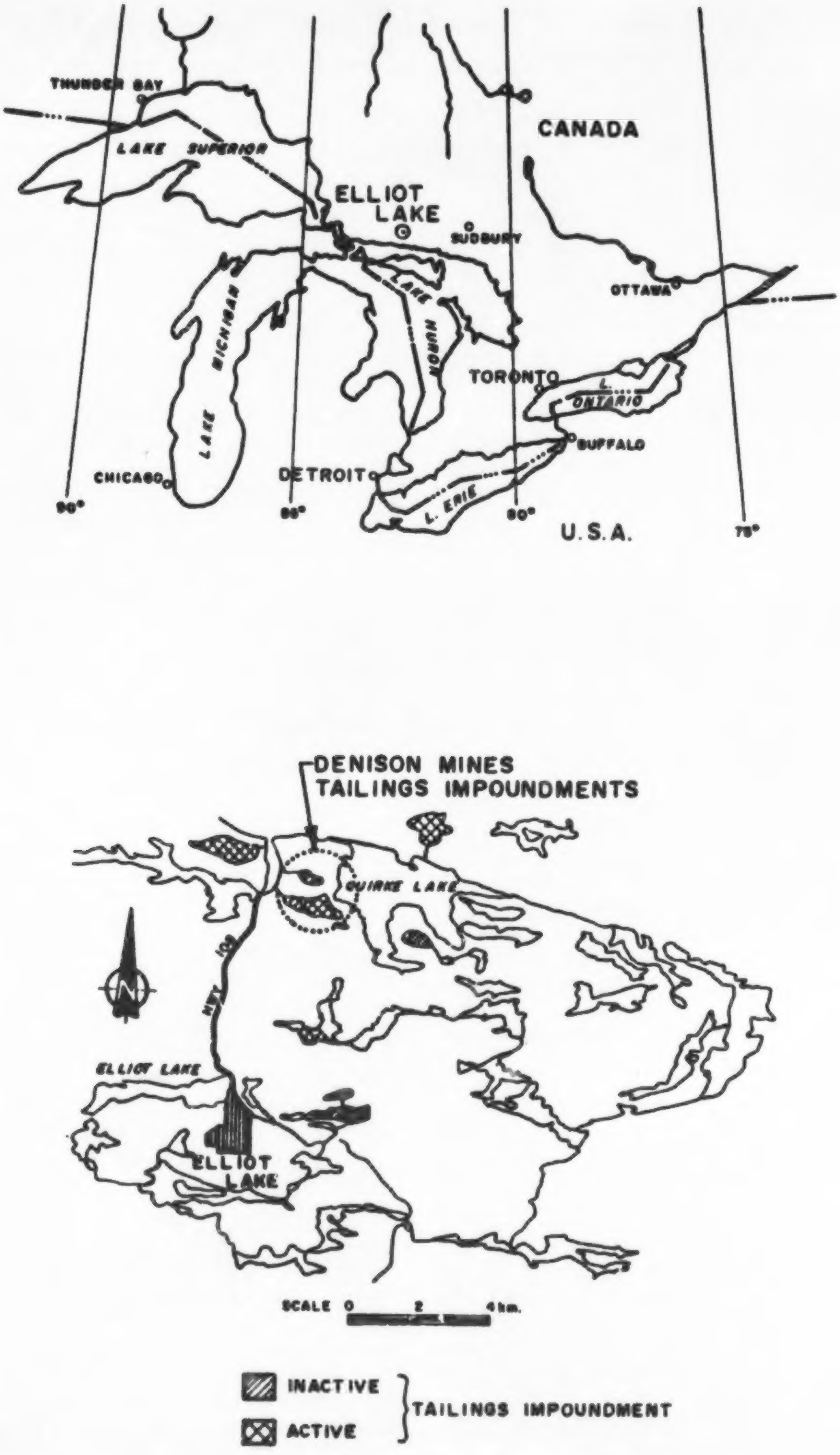
THUNDER BAY
LAKE SUPERIOR
CANADA
ELLIOT LAKE
SUDBURY
OTTAWA
LAKE MICHIGAN
LAKE HURON
TORONTO
L. ONTARIO
BUFFALO
CHICAGO
DETROIT
L. ERIE
90°
85°
80°
75°
U.S.A.
DENISON MINES TAILINGS IMPOUNDMENTS
QUIRKE LAKE
HWY 108
ELLIOT LAKE
ELLIOT LAKE
N
SCALE 0 2 4 km.
INACTIVE
ACTIVE
TAILINGS IMPOUNDMENT

Fig. 8.1 – Location of Denison Mines tailings impoundments

the design of appropriate procedures for the future long-term decommissioning or 'close-out' of uranium tailings impoundments.

8.2.2 Tailings Solids Sampling

For the purpose of tailings solids sampling, three (3) boreholes were put down in March of 1980 along the axis of the tailings impoundment at the locations shown in Fig. 8.2. Winter access was necessary due to the extremely soft nature of the surface of the tailings. The boreholes were advanced to depths of between 7.0 m and 12.6 m below tailings surface using a skid-mounted diamond drill rig operating from the frozen surface of the tailings. The boreholes were advanced through the tailings by wash boring techniques utilizing H-size casing to a depth where refusal was encountered.

Semi-continuous core samples of the tailings were recovered by piston sampling techniques as the boreholes were advanced. A total of thirty-one individual tailings samples were recovered using this technique. The samples were sealed inside the piston sampler tubes with paraffin wax and transported to a laboratory for analysis. The samples were then extruded in the laboratory and logged to determine the tailings stratigraphy. A total of nineteen samples were selected for sieve, hydrometer and water content analyses and chemical analyses.

The tailings core samples were chemically analysed for water leachable sulfate to determine the gypsum content; acid soluble iron and manganese to determine the oxyhydroxide mineral content; pyrite content; total carbonate mineral content; and cation exchange capacity.

The results of the chemical analyses of the tailings samples are summarized in Table 8.1. These results indicate that soluble sulfate minerals comprise approximately 3 weight per cent of the tailings solids. The soluble sulfate mineral is predominantly gypsum formed from the lime neutralization of the sulfuric acid leach solution in the mill, with minor amounts of jarosite (Kaiman, 1977).

The pyrite content of the tailings, as indicated by the sulfide analyses, is of the order of 7 weight per cent. The pyrite in the tailings was derived from the pyrite in the original ore. The leachable iron analyses represent the concentration of the iron oxide and oxyhydroxide minerals in the tailings. The relatively small amounts of these minerals in the tailings result from the precipitation of the oxides and oxyhydroxides during the lime neutralization of the mill discharge.

The results of the carbonate analyses indicate small amounts of carbonate minerals in the tailings. The carbonate in the tailings is thought to occur as calcium carbonate from the limestone impurities in the lime used for neutralization of the mill discharge. The remainder of the tailings solids are comprised of quartz, feldspar and alumino-silicate minerals which were present in the original ore. The cation exchange capacity of the tailings is relatively low due to the small amounts of clay minerals in the tailings.

Figure 8.3 shows an example of the variation in carbonate content and cation exchange capacity with depth in the tailings and with the tailings stratigraphy. The concentrations of soluble sulfate, leachable iron, carbonate and the cation exchange capacity increase with decreasing grain size of the tailings (Fig. 8.4). This indicates that gypsum, iron oxyhydroxide and carbonate minerals are more abundant in the fine grain fraction of the tailings and are segregated into the finer grained silty tailings. The cation exchange capacity increases with decreasing grain size due to the larger proportion of clay minerals and larger grain surface area in the finer grained silty tailings. The concentrations of pyrite in the tailings do not, however, increase with decreasing grain size of the tailings.

Table 8.1 – Summary of chemical analyses of tailings solids

Williams Lake Tailings Impoundment 1981
(19 Samples)

	Concentration (wt. per cent)	
Constituent	Range	Mean
Soluble sulfate (as SO_4)	0.18 – 9.9	2.8
Sulfide (as FeS_2)	2.2 – 10.5	7.2
Leachable Iron (as Fe)	0.08 – 1.33	0.5
Carbonate (as $CaCO_3$)	<0.003 – 0.4	0.06
Cation Exchange Capacity (meq/100g)	0.75 – 15.7	2.9

From Feenstra et al. (1981).

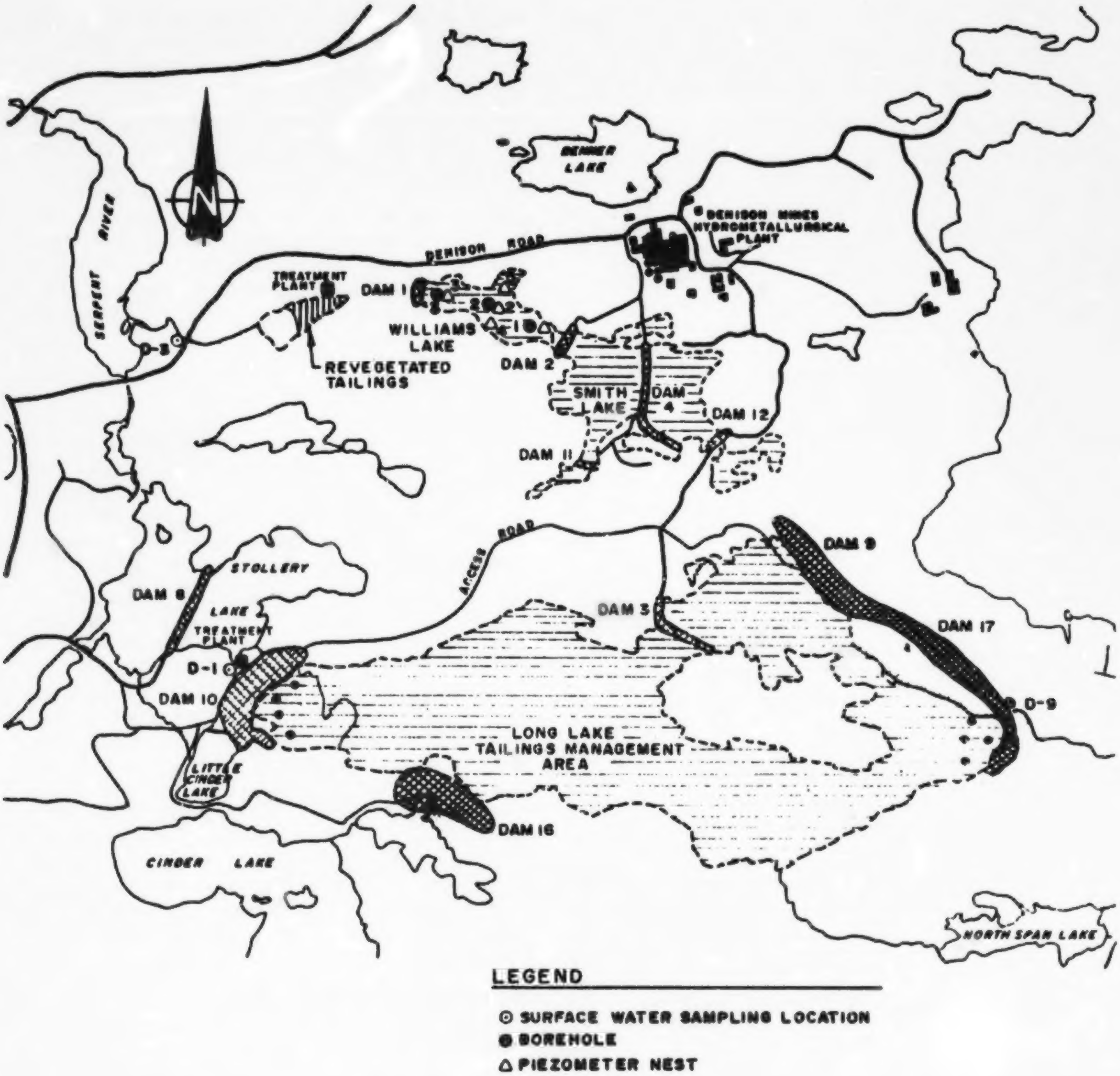
N
SERPENT RIVER
DENISON ROAD
LAKE
DENISON MINES HYDROMETALLURGICAL PLANT
TREATMENT PLANT
DAM 1
WILLIAMS LAKE
REVEGETATED TAILINGS
D-3
DAM 2
SMITH LAKE
DAM 4
DAM 12
DAM 11
ACCESS ROAD
DAM 9
STOLLERY LAKE
DAM 8
TREATMENT PLANT
DAM 3
DAM 17
D-1
DAM 10
D-9
LONG LAKE TAILINGS MANAGEMENT AREA
LITTLE CINDER LAKE
DAM 16
CINDER LAKE
NORTH SPAN LAKE
LEGEND
⊙ SURFACE WATER SAMPLING LOCATION
● BOREHOLE
△ PIEZOMETER NEST

Fig. 8.2 – Williams Lake and Long Lake tailings impoundments

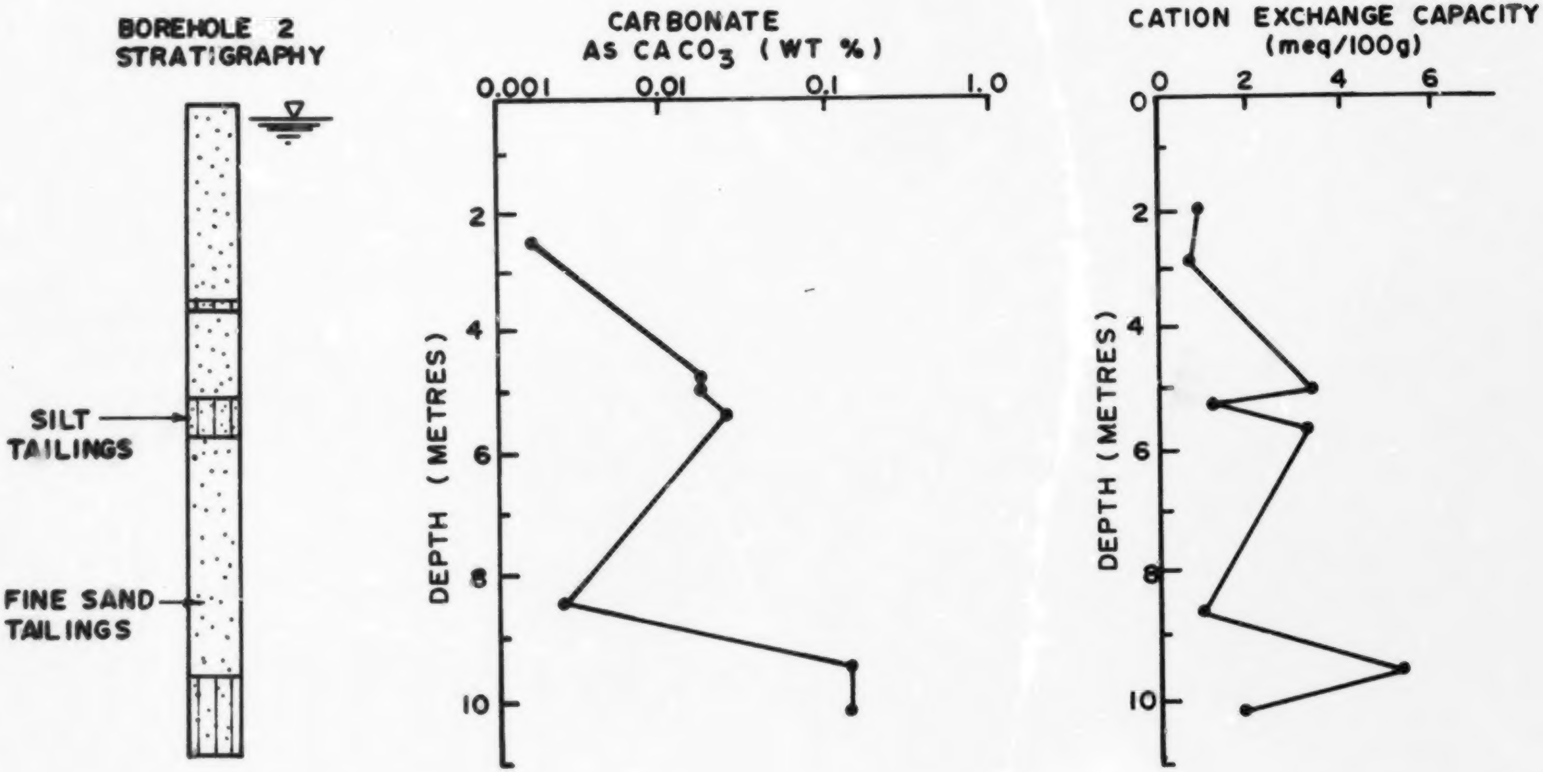

Fig. 8.3 – Example of tailings stratigraphy and tailings solids chemistry – Williams Lake

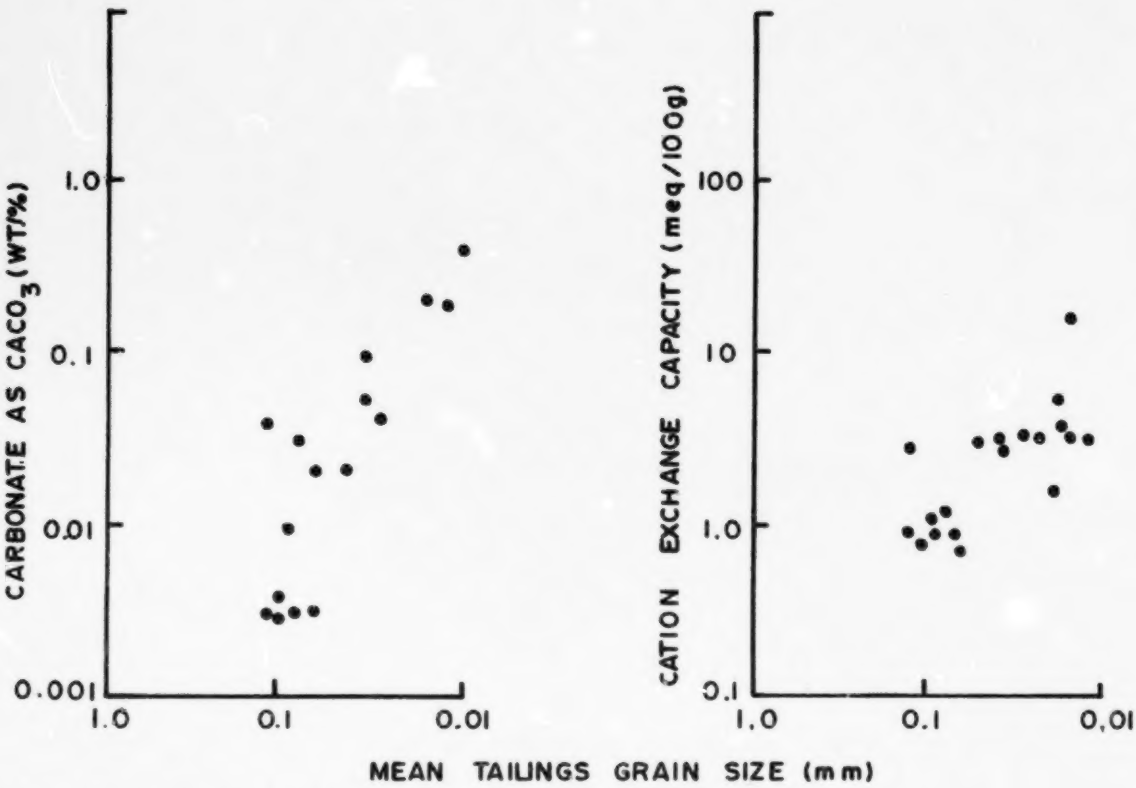

Fig. 8.4 – Chemical composition of tailings solids versus tailings grain size – Williams Lake

8.2.3 Surface Water Sampling

The quantity and quality of surface water runoff from the Williams Lake tailings impoundment is monitored downstream of Dam No. 1 and the treatment plant (see Fig. 8.2). Samples are collected according to the following schedule:

Frequency	*Type*	*Parameter*
Daily		Flow
Daily	Grab	pH
Weekly	Grab	TSS
Weekly	Composite	TDS, iron alkalinity, acidity, nitrate, ammonia, dissolved radium-226
Monthly	Composite	Total radium-226
Every 4 Months	Grab	Sulfate, chloride, potassium, calcium, magnesium, sodium, barium, copper, nickel, lead, cobalt, zinc, and manganese.

The results of this monitoring are reported annually by Environment Ontario in their compilation of Serpent River Basin Water Quality Data. The results of the 1981 monitoring are shown in Table 8.2.

The surface water runoff downstream of the Williams Lake tailings impoundment represents surface water runoff from the tailings and surrounding catchment area, direct precipitation, and seepage from the tailings impoundment through Dam No. 1. Before treatment, this runoff is characterized by low pH and high concentrations of iron, acidity and radium-226. Treatment of the runoff involves the addition of lime and barium chloride to increase the pH and decrease iron, acidity, and radium concentrations. The results of monitoring the treated runoff indicate that treatment is generally effective at controlling pH, iron, acidity and radium. There is a wide variation in the concentration of many parameters due to the varying effects of dilution by precipitation and uncontaminated runoff from the surrounding catchment area.

8.2.4 Piezometer Installation

During the spring of 1980, five nests of piezometers were installed in the Williams Lake tailings impoundment for the purpose of hydraulic head measurement, hydraulic conductivity testing and tailings porewater sampling. The locations of the piezometer nests are shown in Fig. 8.2. Each piezometer nest consists of ten piezometers with the exception of PN-3 which consists of nine piezometers (see Fig.

Table 8.2 – Example of results of surface water sampling – Williams Lake tailings impoundment Stn D-3 downstream of impoundment and treatment plant – 1981

Parameter	Mean	Range	Number of Samples
Flow (L/s)	6.7	0 – 140	180
pH	9.1	7.0 – 11.0	234
TSS	3	<1 – 28	49
TDS	700	74 – 1570	50
Iron	0.50	<0.02 – 1.5	50
Alkalinity	85	25 – 370	51
Acidity	2	0 – 56	51
Nitrate	3	<1 – 8	50
Ammonia	2	<1 – 8	52
Total Radium (Bq/L)	0.74	0.23 – 1.49	13
Diss. Radium (Bq/L)	0.48	0.12 – 1.60	51
Sulfate	370	290 – 510	3
Chloride	150	140 – 167	
Potassium	14	1.3 – 27	2
Calcium	90	30 – 198	3
Magnesium	0.97	0.95 – 1.0	3
Sodium	191	191	1
Barium	0.4	<0.2 – 0.8	3
Copper	0.02	<0.01 – 0.03	3
Nickel	<0.04	<0.04	2
Lead	0.005	0.005	2
Cobalt	0.02	<0.02 – 0.02	2
Zinc	0.03	<0.01 – 0.05	3
Manganese	0.06	<0.02 – 0.12	3

All concentrations in mg/L
Alkalinity and acidity expressed as mg/L $CaCo_3$
Nitrate and Ammonia expressed as mg/L as N.

From Environment Ontario (1981 a).

8.5). Individual piezometers were installed to depths of 0.3 to 8.5 m below the tailings surface. Piezometers consisted of 3.2 cm diameter PVC drive-point piezometers with porous polyethylene intakes (see Fig. 6.2). This type of piezometer was used to allow the use of syringe sampling techniques for the collection of porewater samples with high ferrous iron concentrations, and to allow the installation of the piezometers manually without the use of a drill rig due to the poor accessibility of the tailings to heavy equipment in the non-winter months.

The piezometers were installed manually using a vibration technique with a hand-operated, gasoline powered rock drill (Atlas-Copco 'Cobra'). The piezometer points were advanced to the desired depth by driving coupled 1.5 m long sections of Schedule 40 PVC pipe. A steel driving mandrel formed an adaptor for the rock drill and provided the rigidity for driving the PVC pipe. The tailings below the water table liquified around the piezometer tip during driving, allowing the piezometer to be advanced readily.

Following installation of the piezometers, hydraulic head was measured periodically using an electric sounding tape to determine the directions of porewater flow. Rising-head response tests were conducted in 12 of the piezometers to determine the hydraulic conductivity of the tailings (see Fig. 6.7).

The western portion of the Williams Lake tailings impoundment is covered by a shallow headpond adjacent to Dam No. 1. The water table in the eastern portion of the tailings impoundment occurs within 0.3 m of the surface of the tailings. The water table approximately follows the surface of the tailings sloping from east to west, representing a horizontal hydraulic gradient of 0.5 per cent. Vertical hydraulic gradients within the tailings are approximately 1.5 to 2.5 per cent and are generally downward throughout the tailings impoundment. An example of the vertical hydraulic head profiles is shown in Fig. 8.6. Upward hydraulic gradients can occur in the vicinity of Dam No. 1 when the headpond levels are low. These hydraulic gradients indicate that porewater within the tailings flows predominantly from east to west and vertically downward into the tailings. During periods when the headpond levels are low, tailings porewater discharges to the surface and contributes to surface water runoff from the tailings impoundment.

The horizontal hydraulic conductivity of the tailings measured by the rising-head tests ranged from 10^{-4} cm/s in sandy tailings to 10^{-6} cm/s in silty tailings.

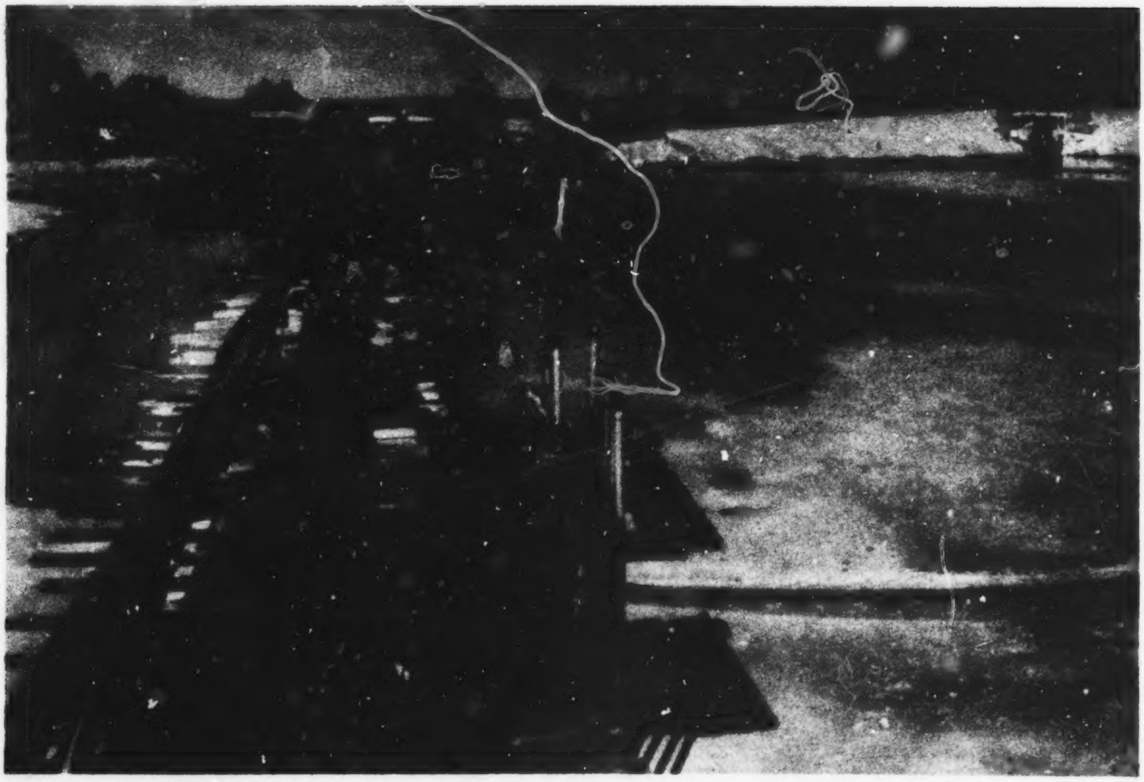

Fig. 8.5 – Example of piezometer nest at Williams Lake

Because the hydraulic gradients within the tailings impoundments are generally small, and the hydraulic conductivity of the tailings is relatively low, the movement of porewater through the tailings is correspondingly slow. Tailings porewater velocities are approximately 0.5 cm/year to 20 cm/year.

8.2.5 Tailings Porewater Sampling

Tailings porewater samples were collected from 36 of the 49 piezometers installed in the Williams Lake tailings impoundment. Each piezometer was purged completely using a suction-lift pump and allowed to refill overnight prior to collection of the samples. Porewater samples were recovered from the piezometers using a down-the-hole syringe sampling device (see Fig. 6.11). The syringe sampler was fitted with a 25 mm diameter filter holder with a 0.45 μm filter membrane so that the porewater samples were filtered in the piezometer as the syringe filled. The porewater samples were retained in the 50 mL syringes and were tightly capped to prevent exposure to the atmosphere. The porewater samples were kept in an ice chest following collection and were delivered directly to the Denison Mines Analytical Laboratory for analysis.

The pH and electrical conductance of the porewater samples were measured in the field at the time of sampling. The samples collected for the analysis of alkalinity, acidity, total dissolved solids, nitrate, nitrite, ammonia, chloride and fluoride were delivered to the laboratory for immediate analysis without the addition of preservatives. The water samples collected from each piezometer for the analysis of major cations (calcium, magnesium, sodium, potassium, aluminum, silicon), heavy metals (manganese, cobalt, nickel, copper, lead, zinc, total iron and ferrous iron) and sulfate were preserved with 0.5 mL of concentrated hydrochloric acid. Samples of tailings porewater were also collected from selected piezometers for the analysis of radium-226. This sampling involved the collection of 1 L porewater samples which were filtered immediately through 142 mm diameter 0.45 μm filter membranes and were preserved with 10 mL of concentrated hydrochloric acid.

Two types of porewater occur in the tailings and can be identified according to their chemical composition. The tailings porewater which occurs near the bottom of the tailings in the Williams Lake tailings impoundment is characterized by neutral pH (6-7), low concentrations of ferrous iron (<100 mg/L) and moderate concentrations of sulfate (1500 – 2500 mg/L). The chemical composition of this porewater closely resembles that of the original mill process water discharge. The chemical composition of this 'original

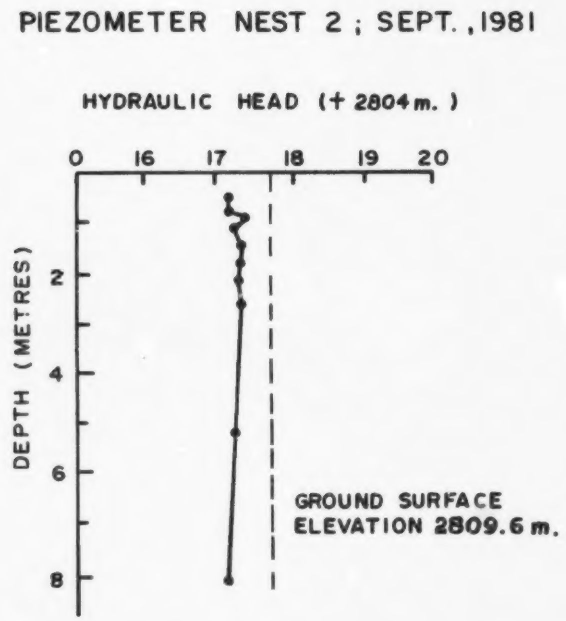

Fig. 8.6 – Hydraulic head vertical profile – Williams Lake

process water' has not been substantially altered by geochemical processes in the tailings.

The tailings porewater which occurs close to the water table in the tailings is characterized by low pH (2-6), and high concentrations of ferrous iron (200-2500 mg/L) and sulfate (2500-6500 mg/L). This porewater represents water which has recharged into the tailings impoundment since the deposition of tailings ended. The chemical composition of this porewater has been substantially altered by the oxidation of pyrite in the tailings.

The extent of movement of 'recharge water' into the tailings is dependent on the nature of the tailings materials and the hydraulic gradients. Where there are small downward hydraulic gradients, the 'recharge water' has penetrated into the tailings to depths of 1.5 m to 4.6 m below the surface of the tailings. These depths of penetration correspond to vertical porewater velocities of 7 cm/year to 23 cm/year. Such velocities are comparable to those calculated from the hydraulic gradient-hydraulic conductivity relationships. The depth of penetration of the 'recharge water' into the tailings at a selected piezometer nest is shown in Fig. 8.7.

The pattern of 'recharge water' penetration into the tailings identified at the Williams Lake tailings impoundment is also identified at the other inactive tailings impoundments at Elliot Lake by Cherry et al. (1980) and Feenstra et al. (1981) in areas where downward hydraulic gradients occur. At other inactive tailings impoundments in areas where the hydraulic gradients are upward, the 'recharge water' does not penetrate into the tailings (Cherry et al., 1980).

The low pH and high concentrations of iron and sulfate in the 'recharge water' in the tailings result in the release of heavy metals such as cobalt, nickel, lead and zinc from the tailings solids into the tailings porewater. The concentrations of these heavy metals are therefore higher in the 'recharge water' in the tailings than in the 'process water'. The results of Moffett and Tellier (1978) and Morin et al. (1982) indicate that the activities of radionuclides such as uranium and thorium are also higher in the low pH 'recharge water' than in the 'process water'.

The activity of radium-226 in the tailings porewater ranges from 1.3 to 6.33 Bq/L at the Williams Lake tailings impoundment. The radium-226 activity in the tailings porewater is not higher in the 'recharge water' than in the 'process water'. The ranges in radium-226 activities determined in the tailings porewater at Williams Lake are comparable to those determined in the other inactive tailings impoundments at Elliot Lake by Cherry et al. (1980).

8.2.6 Wind-blown Dust and Radon

A limited amount of specific information on wind-blown dust and radon for the Williams Lake tailings impoundment was collected during the environmental assessment of uranium mining at Elliot Lake in 1976-1978. Suspended particulate concentrations in air were measured at one location to the east of Williams Lake using a high volume air sampler.

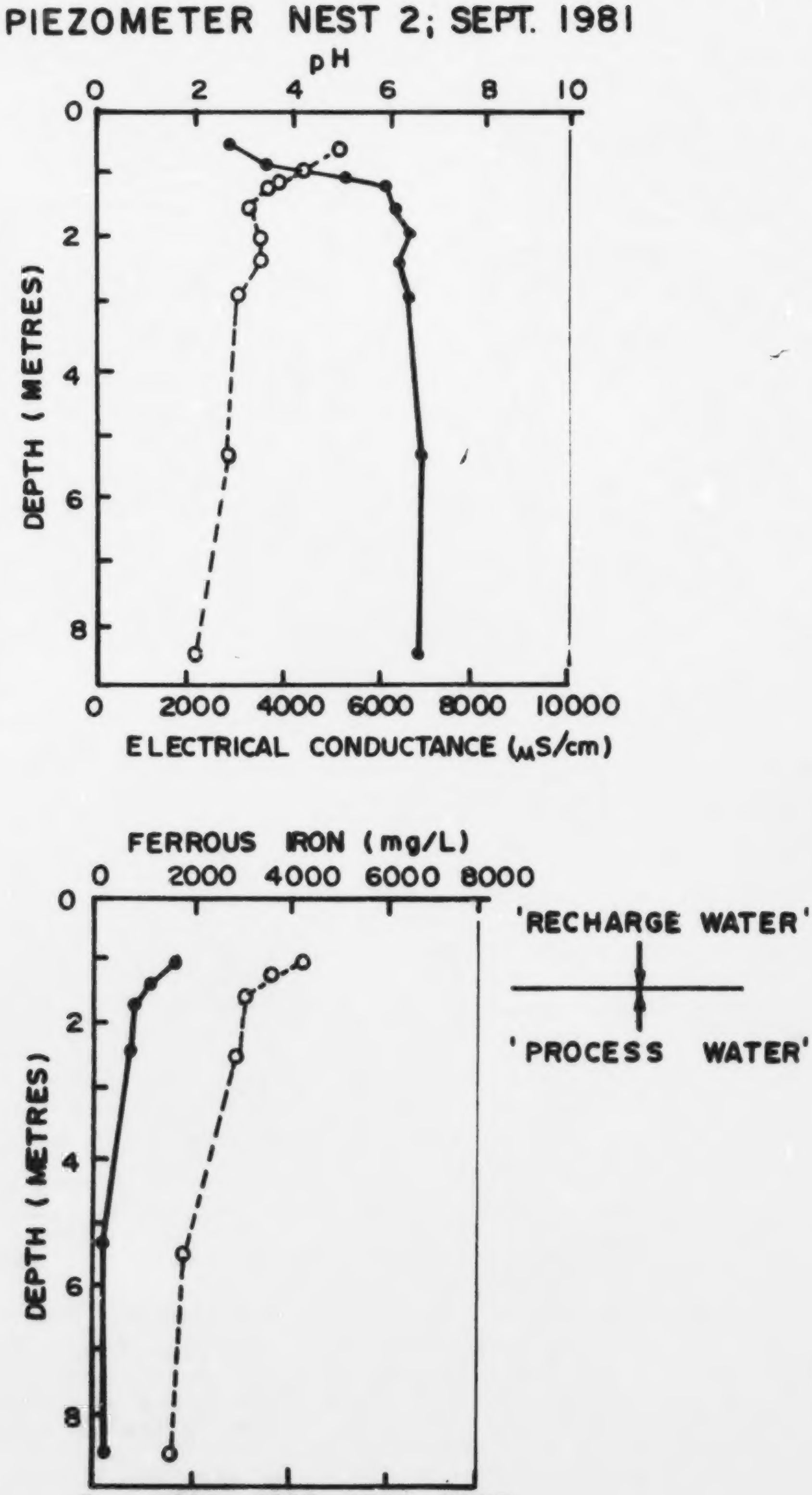

Fig. 8.7 – Porewater chemistry vertical profile – Williams Lake

Ambient radon measurements in air and radon exhalation measurements were conducted on only one occasion at the Williams Lake tailings impoundment. No dustfall measurements were collected specifically for the Williams Lake tailings impoundment. Because of the limited number of air quality and radon measurements for Williams Lake, these data are presented together with those for two other inactive tailings impoundments in the Elliot Lake area (Stanrock and Nordic).

Table 8.3 shows the results of suspended particulate measurements at the Williams Lake, Stanrock and Nordic tailings impoundments together with the federal air quality objectives for suspended particulate.

The geometric mean suspended particulate concentrations at the inactive tailings impoundments are less than federal air quality objectives. Twenty-four-hour concentrations measured at the inactive tailings impoundments occasionally exceed federal guidelines. Suspended particulate concentrations at Williams Lake are considerably lower than Stanrock or Nordic. This difference is likely due to the wet nature of the surface of the Williams Lake tailings compared to the other areas.

A limited radionuclide analysis was conducted on one suspended particulate sample from each of the Stanrock and Nordic tailings impoundments. Similar results would be expected for suspended particulate at Williams Lake. The results of these analyses are shown in Table 8.4 together with the Derived Air Concentration (DAC). All observations are well below the appropriate DAC levels.

Dustfall measurements are not available for the Williams Lake tailings impoundment but are available for the Stanrock and Nordic impoundments. Because suspended particulate concentrations in the air at the Williams Lake tailings impoundment are somewhat less than at Stanrock and Nordic, dustfall at Williams Lake would also be expected to be less. The results of the dustfall measurements are shown in Table 8.5. Only limited data are available on radionuclide levels in dustfall collected near these tailings impoundments. These data are shown in Table 8.6.

Normal background radon levels measured in many areas of the world typically range from 0.0037 to 0.037 Bq/L (UNSCEAR, 1977). One ambient radon measurement (grab sample) was made at the Williams Lake tailings impoundment, however the levels were not detectable. For reference purposes Table 8.7 has been prepared to summarize the available data on ambient radon, ambient radon daughter and radon exhalation measurements for two other inactive tailings impoundments (Stanrock and Nordic). Additional data are expected to become available through on-going research by CANMET (Bigu et al., 1982).

Table 8.3 – Suspended particulate results for Williams Lake and other inactive tailings impoundments

		24-hour	
		S P M	(μg/m^3)
Tailings Area	No. of Samples	Geometric Mean	Range
Williams Lake[1]	13	26	4 – 240
Stanrock[2]	90	40	6 – 1050
Nordic[3]	139	26	0 – 1965

	Federal Air Quality Objectives		
Suspended Particulate Level (μg/m^3)	Maximum Desirable	Maximum Acceptable	Maximum Tolerable
Annual Geometric Mean	60	70	—
24-hour Concentration	—	120	400

From James F. MacLaren Ltd. (1978).

Sampling Stations:

1) Long Lake No. 1 – 50 m from tailings

2) Stanrock No. 1, No. 2, and No. 3 – 100, 100 and 250 m from tailings respectively

3) Nordic No. 1 and No. 2 – 100 and 200 m from tailings respectively.

Table 8.4 – Radiological analyses of suspended particulate samples collected near inactive tailings impoundments

		Inactive Tailings Areas			
Sample station and date		Stanrock No. 1 – June 21		Nordic No. 1 – July 25	
Particulate concentration		1050 µg/m^3		1970 µg/m^3	
Radionuclide	DAC	Radionuclide analyses			
	Bq/m^3	Bq/g	Bq/m^3	Bq/g	Bq/m^3
Lead-210	1.23×10^3	11	1.1×10^{-2}	5.1	1.0×10^{-2}
Polonium-210	2.12×10^3	8.2	8.6×10^{-3}	1.2	2.4×10^{-3}
Radium-226	2.17×10^3	N.D.	N.D.	0.66	1.3×10^{-3}
Thorium-230	5.81×10^1	0.022	3.7×10^{-5}	2.6×10^{-2}	3.7×10^{-5}
Thorium-232	$<1.45 \times 10^1$	4×10^{-3}	4×10^{-5}	1.1×10^{-2}	3.7×10^{-5}

DAC – Derived Air Concentration calculated from dose conversion data for most restrictive form of radionuclide for 1 µm diameter particles. From J.R. Johnson (1983).

Table 8.5 – Summary of total dustfall data collected in the Elliot Lake area during 1976-1980

	No. of Samples Collected					Mean Dustfall Levels (g/m^2/30 days)					Maximum Value (g/m^2/30 days)				
Location	1976	1977	1978	1979	1980	1976	1977	1978	1979	1980	1976	1977	1978	1979	1980
Nordic tailings (South)	1	11	12	11	11	—	2.4	2.1	2.4	1.8	1.1	5.3	5.6	4.7	3.6
Nordic tailings (SE)	—	5	12	12	11	—	6.3	5.1	4.3	2.3	—	14.0	14.5	8.8	11.9
Stanrock tailings (East)	1	9	11	12	11	—	2.4	1.7	2.1	2.0	0.7	6.2	4.2	5.1	4.2
Stanrock tailings (NW)	5	11	12	12	11	2.2	2.1	1.5	1.2	1.5	4.2	4.9	3.1	2.1	9.8
Stanrock tailings (SE)	—	5	12	12	11	—	4.0	4.6	6.1	5.4	—	8.6	11.5	14.0	22.3

From Environment Ontario (1981b).

Table 8.6 – Uranium and radium-226 in dustfall during the 1976-1978 period

	Uranium-238			Radium-226		
Location	No. of samples	No. of samples above DL	Mean of samples above DL (MBq/km^2/30 days)	No. of samples	No. of samples above DL	Mean of samples above DL (mBq/mg)
Nordic S	10	9	0.92	14	8	7.0
Stanrock E	9	3	0.81	13	7	1.8
Stanrock NW	10	6	0.48	17	11	9.3
Nordic SE	6	4	0.44	6	4	6.3
Stanrock SE	7	3	0.33	7	5	6.7

(DL) Detection limits reported as Uranium – 0.185 MBq/km^2/30 days
Radium – 0.37 mBq/mg

From Environment Ontario (1981b).

Table 8.7 – Ambient radon measurements for inactive tailings areas

Area	Location	No. of samples	Radon (mBq/L)	
			Range	Average
Williams Lake spill area	Vegetated tailings	1	–	Not detectable
Nordic	Over tailings	4	81 – 340	170
Stanrock	Over tailings	4	11 – 44	22
	Near tailings	3	3.7 – 19	11
			Radon daughter (WL)	
Nordic	Vegetated tailings	1	–	.0004
	Over tailings	3	0.003 – .0008	.0005
			Radon exhalation (Bq/m^2·s)	
Williams Lake spill area	Vegetated & soil covered	1	–	0.7
Nordic	On tailings	4	4.4 – 14.5	8.70
Stanrock	On tailings	1	–	0.22

From James F. MacLaren Ltd. (1978).

8.3 LONG LAKE TAILINGS IMPOUNDMENT

8.3.1 Introduction

The Long Lake tailings impoundment covers 125 ha and presently contains approximately 40 million tonnes of tailings. The tailings impoundment is enclosed by bedrock ridges to the north and south, and by Dam No. 10 to the west and Dams No. 9 and 17 to the east (see Fig. 8.2). The bedrock ridges consist predominantly of low permeability metamorphosed conglomerates, siltstones and arkoses of the Gowganda Formation. The tailings in the central portion of the impoundment are currently approximately 25 m in thickness. Dam No. 10 consists of earthfill with a low permeability synthetic membrane and is presently 27 m in height. Dams No. 9 and 17 consist of earthfill with low permeability glacial till cores and are approximately 12 m in height.

Because the tailings are discharged to the Long Lake tailings impoundment from the east end, the surface of the tailings slopes from east to west at a grade of approximately 0.5 per cent, and sandy tailings predominate in the east end of the impoundment while silty tailings predominate in the west end.

The continual discharge of tailings to the impoundment (260 L/s liquid effluent – 1983) ensures that the tailings remain wet. The surface of the tailings is extremely soft and is inaccessible even on foot except on the coarse sandy tailings immediately adjacent to the tailings discharge.

Various sampling programs have been implemented at the Long Lake tailings impoundment for a variety of purposes. These programs have included tailings discharge and decant sampling as part of Denison Mines routine monitoring; determination of in situ physical properties of the tailings; tailings porewater sampling as part of a continuing program directed toward the design of appropriate procedures for the future 'close-out' of uranium tailings impoundments; and wind-blown dust and radon sampling as part of the 1977-1978 environmental assessment of uranium mining at Elliot Lake.

8.3.2 Physical Properties of Tailings

During the late fall of 1978 and winter of 1979 a total of 8 boreholes were put down in the Long Lake tailings impoundment to determine the density of the tailings deposited in the impoundment. The density of tailings 'as deposited' is an important consideration in assessing the remaining capacity of an active tailings impoundment. Four boreholes were put down in the silty tailings adjacent to Dam No. 10, and 4 boreholes were put down in the mixed sandy and silty tailings adjacent to Dam No. 17. Samples of tailings were recovered using a thin-walled fixed piston sampler. The tailings samples were weighed in the field immediately upon recovery from the boreholes, the lengths of the recovered samples measured and the samples carefully sealed with paraffin wax. Water content, bulk density and dry density were determined in the laboratory. In situ vane tests were conducted in one borehole at both Dam No. 10 and Dam No. 17 to determine the undrained shear strength of the tailings.

The results of the sampling program are shown in Fig. 8.8. The silty tailings at both Dams No. 10 and No. 17 show distinct decreases in water content and increases in tailings density with depth. These trends likely result from the compaction of the deeper tail-

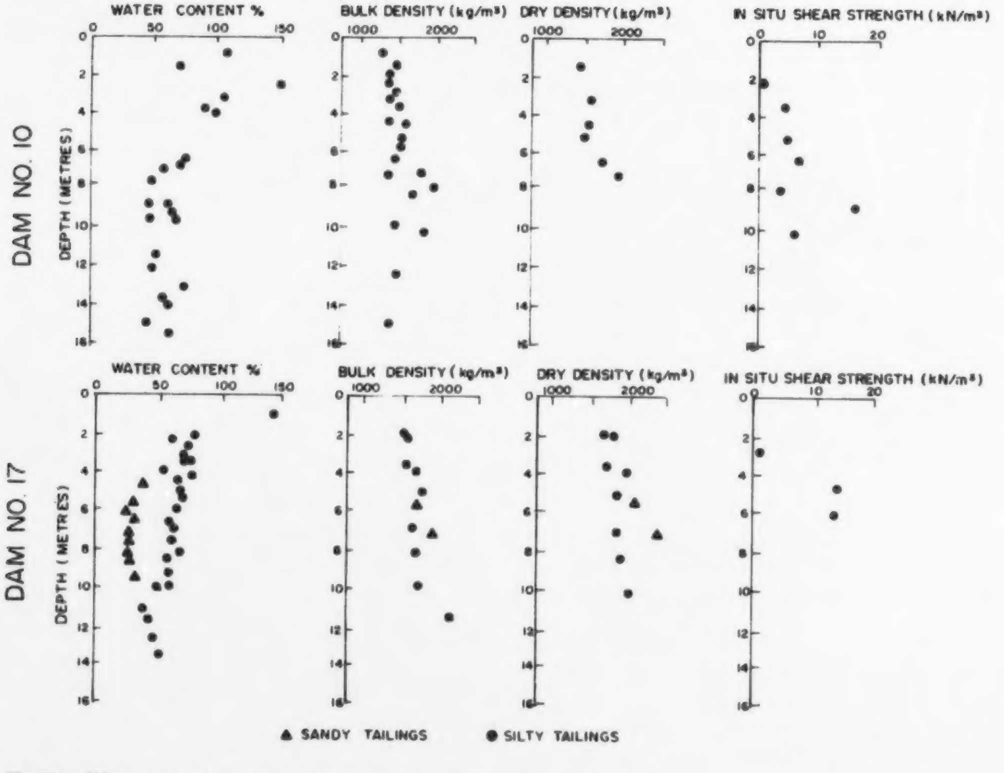

Fig. 8.8 – Water content, density and in situ shear strength profiles – Long Lake

ings by the weight of the overlying tailings. As the tailings density increases, the in situ shear strength also increases with depth.

8.3.3. Tailings Discharge, Decant and Seepage Sampling

The quantity and quality of tailings discharge to, decant and seepage from the Long Lake tailings impoundment are monitored routinely. Samples are collected according to the following schedule:

Tailings Discharge (Liquid effluent)

Frequency	*Type*	*Parameter*
Monthly	Grab	pH, TDS, ammonia, nitrate, nitrite, magnesium, dissolved radium-226.
Yearly	Grab	Sulfate, copper, lead, zinc, nickel, cobalt, manganese, calcium, potassium, chloride, iron, sodium.
Tailings Discharge (Solids)		
Monthly	Grab	Uranium, thorium, radium total sulphur.
Tailings Decant		
Daily		Flow
Daily	Grab	pH
Weekly	Grab	TSS
Monthly	Composite	Total radium-226
Seepage Ditch at Dam No. 17		
Monthly		Flow
Monthly	Grab	pH, TDS, alkalinity, acidity, dissolved radium-226.

The results of this monitoring are reported annually by Environment Ontario in their compilation of Serpent River Basin Water Quality Data and by Denison Mines in their Annual Safety Reports. Examples of typical results are shown in Tables 8.8 and 8.9.

The tailings discharge (Table 8.8) represents the general water quality of the porewater contained within the tailings. The tailings porewater is therefore characterized by high pH, high radium activities and moderately high concentrations of total dissolved solids. The tailings decant quality (Table 8.9) represents the general water quality of surface water runoff from the tailings impoundment. The decant water quality is comparable to that of the tailings discharge but has substantially lower activities of radium-226. The lower radium-226 activities in tailings porewater in inactive tailings impoundments and similarly the lower activities in the tailings decant have been attributed to adsorption and co-precipitation reactions within the tailings (Feenstra et al., 1981). The tailings decant is treated with barium chloride to further reduce radium-226 activities prior to discharge.

The water quality of the seepage ditch at Dam No. 17 (Table 8.9) is considerably different than that of the tailings porewater. The pH is generally neutral and the total dissolved solids concentrations are a factor of 10 or more lower than the tailings porewater. Consequently, it was evident that there was no significant seepage of tailings porewater through the retaining dam in this area during 1981.

8.3.4 Tailings Porewater Sampling

During the late fall of 1981, tailings porewater samples were collected at five locations in the east end of the Long Lake tailings impoundment. These tailings porewater samples were collected in order to determine any effects of pyrite oxidation in the active tailings impoundment.

The sampling was conducted when the upper 10-15 cm of the tailings were frozen to allow safe access on foot. Normally the surface of the tailings is too soft to allow any access. Porewater samples were collected from the water table from shallow hand-dug pits. Piezometers or other permanent monitoring devices were not installed in this case because they would be generally inaccessible. pH and electrical conductance measurements were made in the field immediately following sample collection.

In general, the pH and electrical conductance of the tailings porewater closely resembled that of the tailings discharge. The only exception to this was in an area of sandy tailings behind the current location of the tailings discharge pipe across which neutralized tailings discharge no longer flows. In this area, the pH of the tailings porewater was 3.9 and the electrical conductance was higher than the tailings discharge, indicating the effects of some degree of pyrite oxidation.

These results indicate that although pyrite oxidation does not occur extensively in active tailings impoundments, it can occur in localized zones which are isolated from a continual input of neutralized tailings discharge.

8.3.5 Wind-blown Dust and Radon

A limited amount of information on wind-blown dust and radon for the Long Lake tailings impoundment was collected during the environmental assessment of uranium mining at Elliot Lake during 1976-1978. Suspended particulate, dustfall, ambient radon and radon exhalation measurements were conducted at

Table 8.8 – Example of tailings discharge to Long Lake tailings impoundment – 1982

Liquid effluent

Parameter	Mean concentration
Flow (L/s)	260
pH	9.2
TDS	3876
Dissolved Radium (Bq/L)	73.9
Iron	0.42
Sulfate	1400
Ammonia	83
Nitrate	139

Concentrations in mg/L.
Ammonia and nitrate expressed as mg/L as N.

Solids

Parameter	Mean concentration
Uranium (as U_3O_8)	0.0093%
Thorium (as ThO_2)	0.046%
Radium (Bq/g)	8.3
Total sulphur	4.24%

Denison Mines Limited Annual Safety Report – 1982.

Table 8.9 – Example of results of surface water sampling – Long Lake tailings impoundment – tailings decant

STN D-1 1982

Parameter	Mean concentration
Flow (L/s)	289
pH	8.9
TSS	13.2
Total radium (Bq/L)	25.6

From Denison Mines Limited Annual Safety Report – 1982

Seepage ditch at Dam No. 17
STN D-9 1981

Parameter	Mean concentration
Flow (L/s)	2.3
pH	7.4
TDS	290
Alkalinity	120
Acidity	5
Total radium (Bq/L)	0.015

All concentrations in mg/L.
Alkalinity and acidity expressed as mg/L $CaCO_3$.

From Environment Ontario (1981a).

the Long Lake tailings impoundment. Because of the limited number of measurements available, these data are presented together with those from the active Quirke tailings impoundment for comparison purposes.

The results of the suspended particulate measurements are shown in Table 8.10. The geometric mean suspended particulate concentrations at both tailings impoundments are below federal air quality guidelines. All 24-hour suspended particulate concentrations at the Long Lake impoundment are below federal air quality guidelines. Radionuclide analyses of suspended particulate samples are shown in Table 8.11. All suspended particulate radionuclide levels are below calculated DAC levels.

Total dustfall data are available for 3 locations at the Long Lake tailings impoundment. Dustfall levels were measured by Denison Mines Limited during 1979-1980. These data are shown in Table 8.12. All of the results are well below the provincial standard of 7 g/m^2/30 days.

Ambient radon, ambient radon daughter and radon exhalation measurements at the active tailings impoundments are shown in Table 8.13.

Table 8.10 – Suspended particulate results for active tailings impoundments

Tailings Area	No. of Samples	24-hour S P M $\mu g/m^2$	
		Geometric mean	Range
Long Lake[1]	28	16	1 – 262
Quirke[2]	74	33	1 – 441

From James F. MacLaren Ltd. (1978).

Sampling Stations :

1) Long Lake No. 2 and No. 3 – 50 and 1000 m from tailings respectively

2) Quirke No. 1, No. 2 and No. 3 – 120, 20 and 1000 m from tailings respectively

For Air Quality Objectives see Table 8.3.

Table 8.11 – Radionuclide analyses of suspended particulate samples collected near active tailings impoundments

Sample Station and Date		Active Tailings Areas			
		Quirke No. 1 – July 17, 20, 23, 24, 27		Long Lake No. 1 – Sept. 9 No. 2 – Sept. 16 No. 3 – Sept. 17	
Mean particulate concentration		87 $\mu g/m^3$		206 $\mu g/m^3$	
Radionuclide	DAC	Radionuclide analyses			
	Bq/m^2	mBq/g	$\mu Bq/m^3$	mBq/g	$\mu Bq/m^3$
Lead-210	1.23×10^3	210	18	270	56
Polonium-210	2.12×10^3	120	11	220	44
Radium-226	2.17×10^3	815	70	0	2.7
Thorium-230	5.8×10^1	2.9	0.27	5.2	11
Thorium-232	1.45×10^1	0.81	1.4	11	2.7

DAC – Derived Air Concentration calculated from dose conversion data for the most restrictive form of radionuclide for 1 µm diameter particles.

From James F. MacLaren Ltd. (1978).

Table 8.12 – Total dustfall data collected at the Long Lake tailings impoundment by Denison Mines Limited

	Total Dustfall (g/m²/30 days)					
	1979					1980
Site	June	July	August	September	October	May
A	1.8	—	.07	.14	.17	—
B	0.2	0.2	.17	.13	.15	.32
C	0.3	0.1	.10	.12	.16	1.02

Note
— Data Missing
From Environment Ontario (1981b)

Table 8.13 – Ambient radon measurements for active tailings areas

Area	Location	No. of Samples	Radon (mBq/L) Range	Average
Long Lake	Over tailings	7	11 – 140	60
	Near tailings	4	3.7 – 26	15
Quirke	Over tailings	12	85 – 230	40
	Near tailings	4	N.D. – 19	7.5
			Radon daughters (WL)	
Long Lake	Over tailings	6	0.0003 – 0.0009	0.0006
	Near tailings	7	0.0002 – 0.0014	0.0007
Quirke	Over tailings	4	0.0003 – 0.0008	0.0005
	Near tailings	4	0.0002 – 0.0006	0.0004
			Radon Exhalation (Bq/m²/sec)	
Long Lake	Tailings area	6	0.33 – 15.9	4.7
Quirke	Tailings area	6	8.9 – 70.6	29.8

From James F. MacLaren Ltd. (1978)

8.4 SUMMARY

The preceding sections describe various sampling programs conducted at the Denison tailings impoundments. These programs have been implemented for a variety of purposes which include: routine monitoring for compliance with regulatory agencies; environmental impact assessment; and the design of appropriate procedures for future long-term decommissioning or 'close-out' of uranium tailings impoundments.

Routine monitoring of surface water quantity and quality is conducted at both the inactive Williams Lake tailings impoundment and the currently active Long Lake tailings impoundment. Sampling of air quality in the vicinity of the tailings impoundments was conducted during 1976-1978 for the overall environmental impact assessment of proposed uranium mining expansion in the Elliot Lake area. Detailed investigations of the tailings solids and tailings porewater at the Williams Lake tailings impoundment are on-going to provide information for the design of long-term decommissioning procedures for inactive uranium tailings impoundments.

8.5 REFERENCES

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APPENDIX A

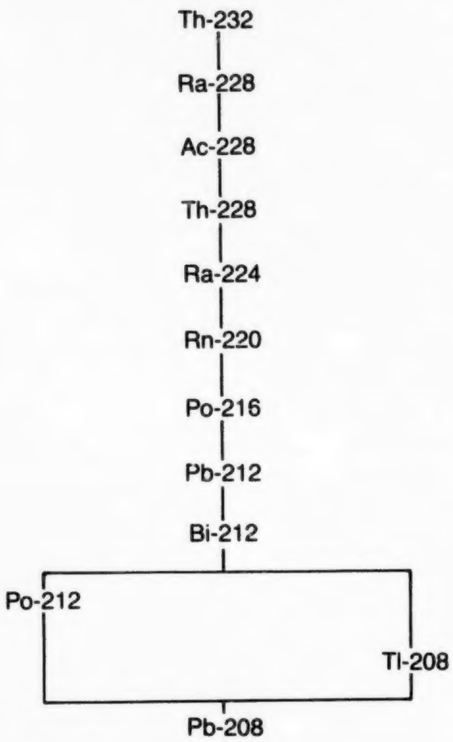
URANIUM-238 AND THORIUM-232 DECAY SERIES

A-1
URANIUM RADIOACTIVE DECAY SERIES

DECAY SEQUENCE	NUCLIDE	HALF-LIFE
U-238	Uranium-238	4.51×10^9 y
Th-234	Thorium-234	24.1 d
Pa-234	Protoactinium-234	1.17 d
Pa-234	Protoactinium-234	6.75 h
U-234	Uranium-234	2.47×10^5 y
Th-230	Thorium-230	8.0×10^4 y
Ra-226	Radium-226	1602 y
Rn-222	Radon-222	3.8 d
Po-218	Polonium-218	3.05 min
Pb-214	Lead-214	26.8 min
At-218	Astatine-218	2 s
Bi-214	Bismuth-214	19.7 min
Po-214	Polonium-214	164 μs
Tl-210	Thallium-210	1.3 min
Pb-210	Lead-210	21 y
Bi-210	Bismuth-210	5.01 d
Po-210	Polonium-210	138.4 d
Tl-206	Thallium-206	4.19 min
Pb-206	Lead-206	Stable

A-2
THORIUM RADIOACTIVE DECAY SERIES

DECAY SEQUENCE


Th-232
Ra-228
Ac-228
Th-228
Ra-224
Rn-220
Po-216
Pb-212
Bi-212
Po-212
Tl-208
Pb-208

NUCLIDE	HALF-LIFE
Thorium-232	1.41×10^{10} y
Radium-228	6.7 y
Actinium-228	6.13 h
Thorium-228	1.910 y
Radium-224	3.64 d
Radon-220	55 s
Polonium-216	0.15 s
Lead-212	10.64 h
Bismuth-212	60.6 min
Polonium-212	304 ns
Thallium-208	3.1 min
Lead-208	Stable